SEE
FOLLOWING
NOTE

VOIR
NOTE
CI-APRÈS

PARTS OF THE ORIGINAL DOCUMENT

ARE OF POOR REPRODUCTIVE QUALITY

CERTAINES PARTIES DU DOCUMENT ORIGINAL

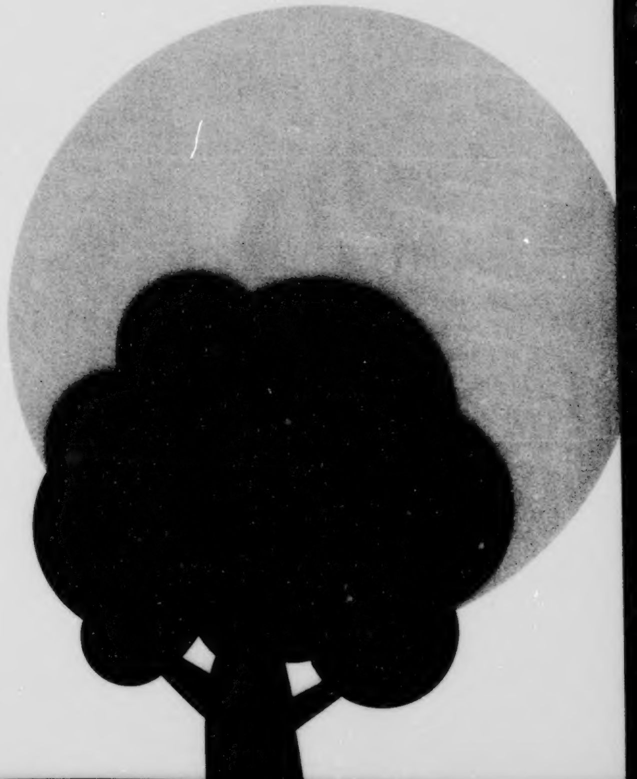
SONT DE PIÈTRE QUALITÉ DE REPRODUCTION

PART

1

Energy, Mines and Resources Canada
Hon. Marcel Masse, Minister

Énergie, Mines et Ressources Canada
L'Hon. Marcel Masse, Ministre



Canada

DESIGN OF A TREE CHIP DRYING SYSTEM
PART I OF II

RENEWABLE ENERGY BRANCH

PREPARED FOR:

Renewable Energy Branch
Energy, Mines and Resources Canada
Ottawa, Ontario

DSS Contract File No: 51SZ.23216-6-6177

September 1987

PREPARED BY:

Intertech Engineering Corporation
199 Bay Street, Suite 503
Toronto, Ontario, Canada M5J 1L4
Telephone (416) 366-2135

SCIENTIFIC AUTHORITY

Dr. W.E. Lowe
Manager, Alternate Energy Development Program
Renewable Energy Branch
Energy, Mines and Resources Canada

1.1 TITLE

DESIGN OF A TREE CHIP DRYING SYSTEM
PART I OF II

RENEWABLE ENERGY BRANCH

PREPARED FOR:

Renewable Energy Branch
Energy, Mines and Resources Canada
Ottawa, Ontario

DSS Contract File No: 51SZ.23216-6-6177

September 1987

PREPARED BY:

Intertech Engineering Corporation
199 Bay Street, Suite 503
Toronto, Ontario, Canada M5J 1L4
Telephone (416) 366-2135

SCIENTIFIC AUTHORITY

Dr. W.E. Lowe
Manager, Alternate Energy Development Program
Renewable Energy Branch
Energy, Mines and Resources Canada

1.2 CITATION

CRINGAN, J.C., ISLES, R., BURRELL, C.,
Intertech Engineering Corporation
Design of a Tree Chip Drying System

Report of Contract File No: 51SZ.23216-6-6177
Renewable Energy Branch; Energy, Mines and Resources Canada
Ottawa, Ontario 1987 (33 pp)

Copies of this report may be obtained through:

Renewable Energy Branch
Energy, Mines and Resources Canada
580 Booth Street
Ottawa, Ontario
K1A 0E4
(613) 995-9447

or

Interlibrary Loans
CISTI Library
National Research Council
Bldg. M-55, Montreal Road
Ottawa, Ontario, K1A 0S2
(613) 993-1585

© Ministre des Approvisionnements et Services Canada 1988

N° de catalogue M91-7/18-1988-1E
ISBN 0-662-16388-5

1.3 ACKNOWLEDGEMENTS

ACKNOWLEDGEMENTS

Intertech Engineering Corporation wish to acknowledge the valuable assistance given by the following individuals, organizations, subcontractors, who were associated with the work of this project.

Dr. W.E. Lowe, Manager, Alternate Energy Development Programme, in the Renewable Energy Branch of Energy, Mines, and Resources, Canada.

Dr. H.A. Becker, Professor and Head of the Chemical Engineering Department, Queen's University.

M. Leboldus. Graduate Student M.Sc. Programme, Department of Chemical Engineering, Queen's University.

DISCLAIMERS

This Report is distributed for information purposes only, and does not necessarily reflect the views of the Government of Canada, nor constitute an endorsement of any commercial product or person. Neither Canada, nor its Ministers. Officers, Employees or Agents. makes any warranty in respect of this Report or asssumes any liability arising out of the Report.

1.4 PREFACE

This report describes the technical and economic details of a design process to achieve an energy efficient wood chip dryer. The work was carried out under the Bioenergy Development Programme of the Renewable Energy Division of Energy Mines and Resources, Canada. The nature of the work centred on the design of heat recovery techniques to minimize the energy consumption of a wood chip dryer and then the optimization of the system under varying conditions of operation in order to determine and compare the real cost of drying wood chips on a unit energy delivered basis.

The intended purpose of the work can be described as follows:-

- Develop new equipment processes, and techniques for economic moisture content reduction of wood chips, whereby the increase in calorific value of the chips due to moisture removal, would significantly outweigh the real cost of processing.
- Prove by detailed cost estimates based on the design of the proposed drying system, the real cost of drying wood chips on a net unit energy delivered basis at varying conditions of product and system operation.

The scope of the work was limited to:-

- processing of tree chips as normally sized for household heating applications
- rating of the system to be 4000 tonnes per year dried basis
- investigation of existing chip drying systems, including the applicability of wind and solar energies
- design of a preferred system to produce economic drying of chips
- analysis of energy, mass flow, and computation of total costs of a preferred drying system including drying, transportation, storage, and combustion
- recommendations for application of the proposed system to other biomass materials.

1.4 Preface cont.

The significant features of the work completed in this project were found to be that

- multiple recovery of heat in a drying system can reduce the energy consumption by a factor of four compared to single pass drying systems
- total energy required to remove one pound of water from wet chips with moisture contents ranging from 50 percent to 25 percent was in the range of 350 BTU
- multiple recovery of heat as a technique in drying systems can be applied to all sorts of commodities for major economies in energy
- net annual savings for residential heating with dried wood chips ranges from $300 to $1000 for small to large homes respectively compared to oil heating.

This report has been prepared with the objective of

- formalizing the work carried out under contract to Energy Mines and Resources
- demonstrating the economic merits of drying tree chips with a regenerative or multi recovery of heat drying system
- providing some cost and construction details of a 4000 tonne per year chip dryer
- acquainting those in both the public and private sectors especially those in the tree chip business with a "state-of-the-art" drying system.

Those using the technical information from this report should be aware of the fact that some but not all of the technology is the proprietary information of Intertech Engineering Corporation since one of their major lines of business is drying technology.

1.5 ABSTRACT

Intertech Engineering Corporation have carried out a study on the Design of a Tree Chip Drying System in accordance with Contract Number 23216-6-6177/01-SZ issued by the Department of Energy, Mines and Resources as part of their Bioenergy Development Programme.

The objectives of the work are:-

- Design and selection of a drying system for wood chips to obtain the lowest cost per tonne of dried product.
- Determination of the drying characteristics of a wood chip dryer in terms of energy required to remove a pound of water at various operating conditions of the dryer, product, and atmosphere.
- Determination of the real cost of drying wood chips on a cost net unit energy delivered basis as compared to costs of wet chips.
- Verification of chip drying characteristics by bench tests.
- Estimation of costs involved in transportation, storage, etc.
- Calculation of fuel burning efficiencies and heating costs.

The work was carried out by review of existing methods for drying tree chips ie. evaluation of the state of the art, followed by preliminary designs of the dryer in the form of drawings. Mass and energy flow balances were then calculated and one of the preliminary designs selected for detail study and evaluation. Detail drawings on the selected design were then prepared along with capital and operating cost estimates. Finally a computer programme was designed to carry out the optimization of the performance of the dryer at various conditions of operation.

The results show that a medium temperature, atmospheric dryer, of the regeneration type with multi stage recovery via a tube in shell heat exchanger and a nominal rating of 2000 pounds per hour of water removal from wood chips can be built and operated with a coefficient of performance (COP) ratio of between 4 and 5. This means that for every heat energy unit used in the process, there will be a four to five fold increase in the heating value of the wood chips

1.5 Abstract cont.

within the range of drying from 50 percent moisture to 25 percent moisture. With regenerative drying of wood chips the fuel cost of residential heating can be reduced from one half to two thirds compared to heating with oil depending on the size of residence.

The results of this project are significant in that it has been demonstrated that the technique of multiple recovery of heat in a drying system can reduce energy consumption by a factor of four compared to single pass drying systems. In addition this technique if applied correctly could be utilized in the drying of all sorts of biomass materials. and as a result would result in major economies in energy consumption.

In the specific case of wood chips in which this project was directed, it was demonstrated that the total energy required to remove one pound of water from wet chips with moisture contents ranging from 50 percent to 25 percent is in the range of 350 BTU.

1.6 TABLE OF CONTENTS

1. FRONT SECTION

1.1 TITLE..(i)

1.2 CITATION.....................................(ii)

1.3 ACKNOWLEDGEMENTS.............................(iii)

1.4 PREFACE......................................(iv)

1.5 ABSTRACT.....................................(vi)

1.6 TABLE OF CONTENTS............................(viii)

1.7 EXECUTIVE SUMMARY............................(ix)

1.8 RESUME.......................................(xvi)

2. CORE SECTION

2.1 INTRODUCTION.................................1

2.2 OBJECTIVES...................................3

2.3 METHOD.......................................4

2.4 RESULTS......................................8

2.5 DISCUSSIONS..................................15

2.6 FIGURES & TABLES.............................19

3. FINAL SECTION

3.1 CONCLUSIONS..................................23

3.2 RECOMMENDATIONS..............................26

3.3 REFERENCES...................................27

3.4 APPENDICES...................................28

Appendix A - Contract Directory Information...........29
Appendix B - Bench Tests on the Drying of Tree Chips..31
Appendix C - Disclosures Certification................32
Appendix D - Computer Analysis of Chip Dryer..........33

1.7 EXECUTIVE SUMMARY

DESIGN OF A TREE CHIP DRYER

This Report describes a regenerative dryer which has been designed by Intertech Engineering Corporation with the assistance of Energy, Mines & Resources. The dryer uses heat recovery techniques which reduce the energy consumption by a factor of four compared to single pass drying systems.

When something becomes dried, the energy that is apparently lost in evaporative cooling, still exists as latent heat. Techniques have been developed for recovering part of the entropic degradation by using a preheat section and repeated recycling of energy through the furnace and a condenser.

Summary

The Intertech Regenerative Dryer uses a horizontal moving bed of chips; 10 cm to 30 cm deep. As the chips progress through the dryer, they pass through zones of progressively higher air temperatures until they reach the primary drying section, and then progressively lower temperatures of secondary drying, emerging at close to ambient temperature. Air travelling spirally in the opposite direction is similarly heated and then cooled before it is exhausted from the cold end of the preheat section.

Energy Recycling

The energy transfers which occur in a dryer show the effects of the law of conservation of energy and the law of entropy. No matter what we do to energy, the energy is still there, but everything we do with energy makes it harder to use in future.

Here is how these laws affect the operation of a regenerative dryer and how the details of the Intertech Dryer make it possible to re-use energy repeatedly and to minimize the losses.

Temperature Degradation

Each time some of the enthalpy in the vapour is converted into sensible heat by condensation, the result is

- a drop in temperature
- a vastly increased mass flow of air, to carry the energy as superheat rather than vapour.

1.7 Executive Summary cont.

The Intertech Dryer uses a small high temperature drying section to produce return air at near the boiling temperature and nearly saturated, so that the resultant secondary heat from the condenser can be at a range of temperatures from slightly below boiling down almost to ambient. The retention time for chips in the dryer is adjusted to dry them adequately at these intermediate temperatures.

At a typical condensing air temperature of 70°C, when 1 kg of saturated air is cooled by 1°, there is sufficient energy transfer to add 1° of superheat to 46 kg of air.

The larger mass flow required in the secondary of a condenser is obtained by using four secondary fans with a total flow capacity many times larger than the primary flow rate.

Multiple Recoveries of the Same Energy

If the primary heat were the only part recycled through the condenser, the maximum amount of secondary heat available would be limited to the primary energy minus the conduction losses and minus the portion of this energy which is at too low a temperature to be of economic use.

In this multiple recovery system an additional quantity of latent heat for recycling comes from the secondary drying zone, where latent heat results from the drying which is done by the secondary heat and by the cooling of the chips. Part of the latent heat at each stage of the secondary heating goes to preheat the chips and part of it works its way up through the four secondary sub zones to become preheated combustion air.

Suppose that the losses in a dryer amount to 0.25 x energy, repeated on each pass through heating and drying.

Then a non-regenerative dryer would have a maximum efficiency of

$$1 - 0.25 = .75 = E \qquad (1)$$

With a single stage of regenerative heat recovery, the performance improves to

$$E + E^2 = 1.31 \qquad (2)$$

1.7 Executive Summary cont.

A circuit providing many recirculations of the energy has a performance coefficient of

$$E + E^{2} + E^{3} = \quad + E^{n} = 3 \qquad (3)$$

The losses could be reduced to less than 0.25 by having a larger, slower and better insulated dryer but a loss ratio of 0.25 is typical for modern drying systems and lower energy losses could involve excessive capital costs.

PREHEATING AND COOLING

Preheating

When an unheated product is dried with hot air

- much of the energy goes into heating the product
- evaporative cooling slows the heating process
- the mass transfer of water in the product is slowed by its low temperature.

In the Intertech Dryer part of the humid return air from the drying heats the green chips without evaporation, making for rapid primary drying and fast transfer of moisture to the surface for the subsequent secondary drying.

Cooling

The Intertech Dryer provides gradual cooling of the chips as they pass through the secondary drying zone. The cooling of the chips is caused by evaporation. This drying is in addition to the evaporation caused by the secondary heat.

Purging the Secondary Zone

If the heat buildup in the secondary zone were allowed to continue unchecked, its humidity would increase and stall the drying. To prevent excessive humidity, there are four sub zones in the secondary drying. In each of these zones the return air has a gradation of humidities, with dewpoint temperatures tracking the falling temperature of the chips.

In each zone, the air with the highest temperature and highest humidity moves up to the next higher zone. From the top secondary drying zone, the air with the highest energy of all goes to the furnace as combustion air for the primary drying.

1.7 Executive Summary cont.

In each of the four sub zones, part of the return air is removed to the preheat zone, replaced by partial recirculation in the secondary drying. Consequently, the air emerging from the partially dried chips will have a high relative humidity but the superheat added at the condenser reduces the r.h. to less than 25%, for effective drying.

COST SAVINGS - CHIPS FOR RESIDENTIAL HEATING

Automatic heating with dried tree chips can reduce the fuel cost of residential heating by from half to two thirds, depending on the price of chips.

Fuel oil costs 29.9 cents/l in Toronto. Burned at 80% efficiency this is a cost of $9.48 per million kJ.

Dried chips at $50/t, yielding 75% of 8750 BTU/lb result in an energy cost of $3.27/million kJ, or proportionately more at higher prices.

Part of the savings in fuel cost are lost in a higher yearly capital cost for an automatic chip burner and a fire resistant chip storage room.

	Large Home	Medium Home	Small Home
Oil per year	2500	1500	1000
Annualized cost of furnace	275	200	150
Total oil cost	2775	1700	1150
Chips per year	862	517	345
Annualized cost/furnace system incl.chip storage	900	665	500
Total htg. cost	1762	1182	845
NET ANNUAL SAVING	1013	518	305
SAVINGS AS PERCENT OF OIL HTG. COST	36%	30%	26%

1.7 Executive Summary cont.

Business Aspects of Chip Burning

In calculating the cost of producing dried chips, we found large differences in the range of costs of each individual component, differences which would have a large effect on the profitability of a chip business.

Eventually, the price of fossil fuels will be so high that that chip business will be viable wherever there is an adequate supply of trees and buildings which need heating. (This is already the established situation in the Scandinavian countries.) The costs can be reduced by a few dollars a ton in situations where there is waste heat available for a dryer at a temperature above the boiling point. and a saving of around $10 per ton can be achieved by using wood processing wastes instead of trees as the source of the chips. During the introductory years, when chip furnaces will usually be imported and the retail market for chips is being developed, the most successful suppliers are likely to be ones who have these cost advantages in raw materials or energy.

An even larger variation in costs involves the amount of output and sales from any given chip business. To build its sales up to the break even point it is very desirable to have an established market for a large part of the output potential, say 50% of it.

Who Can Benefit from Burning of Dried Chips?

Our cost estimates indicate that dried chips at $50 a ton, or even up to $75 a ton, will provide a real saving in heating costs for almost any home, compared to oil heating. However, as long as oil is available and affordable, the net savings in switching to chips must be large enough to hurdle a barrier of human inertia. We would guess that a savings of $100 yearly would not begin to interest anyone. and $1000 would be very interesting to persons in rural areas and towns where wood already supplies some of the heating.

With larger heating systems. the cost savings by using chips becomes larger in dollar value and larger as a percentage of the cost of oil heating. Tree chip heating systems could be extremely attractive for apartment buildings, shopping centres, small factories and very large homes. A number of these users would be a base load for a chip business.

1.7 Executive Summary cont.

COST/BENEFIT ANALYSIS FOR CHIP DRYING

Energy Cost of Dryer Operation

furnace 750,000 kJ/h @ $3.00/million kJ = $2.25/h

electric 150,000 kJ/h @ 5 cents/kWh & 36MJ/kWh = $2.08/h

Total energy cost = $4.37/h

Labour Cost of Dryer Operation

Operations, 2 persons part time (doing other work most of time) = $5.00/h

Servicing, $10,000/yr = $2.00/h

Total operating cost = $11.37/h

Operating cost @ 5t/h = $2.27/t

Capital Cost

The estimated cost of building a 5t/h chip dryer is $155,000. This includes insulated panels, steel framework, internal partitions, a large heat exchanger, a conveyor, fans, a furnace, electrical work and controls, miscellaneous hardware and $25,000 for contingencies.

A further capital investment is needed for a building and material handling equipment to move chips to and from the conveyor. This does not include the cost of field equipment, which is included in the price of green chips. The chip drying plant, including buildings will have a total cost of around $250,000. This can be financed on a mortgage loan with 20 year amortization and interest for $34,000/year.

Based on a planned 5000 hrs. operation yearly, this produces a capital cost of $6.80/h or $1.36/t of chips.

Total operating and capital cost of chip drying = $3.63/t of chips.

1.7 Executive Summary cont.

Value of Chip Drying

Drying of chips for residential heating produces a quantifiable increase in the net heat available per tonne of solids in the chips, plus the essential non quantifiable benefit of making a residential fuel out of something which would otherwise require an industrial furnace.

A chart produced by R.L. Stewart, which has been reproduced in various reports, shows the boiler efficiency of wood varying from 77% at 10% moisture (wet basis) down to 58% at 60% moisture content, wet basis. From this chart and a starting point of a heat value of 8750 BTU/lb. of wood and bark, dry weight, we derived a figure indicating that each 1% of moisture (dry basis) is worth 15 BTU in the heat available from 1 lb of chips. Or in more familiar terms each 1 lb of water removed from a load of chips increases the net heat recovery by 1500 BTU. This represents 1000 BTU needed to vaporize the water in the furnace, plus additional losses due to requiring more air, and losses from incomplete combustion when the furnace gets closer to its blackout point. A further advantage of dried chips is that the heat capacity of a particular furnace can be increased by up to 50% by switching from wet to dry chips.

Net heat from wet chips .6 x 8750 = 5250 BTU/lb.

Net heat from dry chips .75 x 8750 = 6562 BTU/lb.

Extra from drying 1312 BTU/lb. x 2204 = 2.89 MBTU/t of chips.

The previous estimate of $2.27/t drying cost is based on 2700 lb water taken from 5t of product, or 540 lb water per t. or .245 lb water/lb of chips. If there is no natural drying preceding the thermal drying, the cost of operating the dryer could rise to $5.00 per t of chips, or $5.00/2.99 MBTU or a cost of $1.73 per MBTU of heat improvement achieved by the drying. This is much lower than the cost of other energy sources.

A computer program has been written, calculating the mass flows, temperature and enthalpies at ninety different parts of the drying system.

This will enable optimizing the operation of the dryer for variations in temperature and initial moisture content of the chips.

1.8 RESUME

1.7 RÉSUMÉ À L'INTENTION DE LA DIRECTION

CONCEPTION D'UN SÉCHOIR DE COPEAUX

Ce rapport décrit un séchoir régénérateur conçu par Intertech Engineering Corporation qui a reçu l'aide d'Énergie, Mines et Ressources. Le séchoir utilise des techniques de récupération d'énergie qui réduisent la consommation d'énergie au quart de celle d'un système à passage unique.

Quand on fait sécher quelque chose, l'énergie qui semble disparaître en évaporation est toujours là sous forme de chaleur latente. On a mis au point des techniques permettant de récupérer une partie de l'entropie grâce à une section de préchauffage et à la récupération de l'énergie par le générateur d'air chaud et un condenseur.

Sommaire

Le séchoir régénérateur Intertech fonctionne de la façon suivante : un lit de copeaux (d'une épaisseur de 10 à 30 cm) en mouvement traverse des zones dont la température va en augmentant, jusqu'à ce qu'il atteigne la section de séchage primaire. Il subit ensuite un séchage secondaire dans des zones dont la température va en décroissant pour atteindre une température avoisinant celle de la pièce. L'air qui circule en sens inverse en tourbillonnant est aussi chauffé, puis refroidi avant d'être évacué de l'extrémité froide de la section de préchauffage.

Récupération de l'énergie

Le transfert d'énergie qui s'effectue dans un séchoir illustre bien les effets de la loi de la conservation de l'énergie et de la loi de l'entropie : peu importe l'utilisation de l'énergie, elle existe toujours, mais chaque transformation la rend plus difficile à utiliser par la suite.

Nous allons voir comment ces lois s'appliquent au fonctionnement d'un séchoir régénérateur et comment les caractéristiques du modèle Intertech lui permettent de réduire les pertes au minimum et de réutiliser plusieurs fois l'énergie.

Perte de chaleur

Chaque fois qu'une partie de l'enthalpie de la vapeur est convertie en chaleur sensible par condensation, on a comme résultat :

- une chute de la température
- un écoulement d'air considérablement accru, pour acheminer l'énergie sous forme de surchauffe plutôt que de vapeur.

1.7 RÉSUMÉ À L'INTENTION DE LA DIRECTION (suite)

Le séchoir Intertech comporte une petite section de séchage à haute température qui donne de l'air quasi-saturé dont la température avoisine le point d'ébullition de l'eau. Ainsi, la chaleur secondaire tirée du condenseur atteint une température variant entre une valeur légèrement inférieure au point d'ébullition de l'eau et une valeur légèrement supérieure à la température ambiante. La durée du séjour des copeaux dans le séchoir est déterminée de façon à les faire sécher correctement en fonction de la température.

Par exemple, à la température type de 70° C de l'air de condensation, quand 1 kg d'air saturé est refroidi de 1°, le transfert d'énergie est suffisant pour ajouter 1° de surchauffe à 46 kg d'air.

La circulation d'une masse d'air plus importante dans la section secondaire du condenseur est obtenue grâce à quatre ventilateurs qui fournissent un débit total plusieurs fois plus important que celui de la section primaire.

Récupération multiple de la même énergie

Si on ne devait récupérer que la chaleur primaire dans le condenseur, le maximum de chaleur secondaire qu'on obtiendrait serait limité à l'énergie primaire, moins les pertes par conduction, moins la partie irrécupérable (à un coût économique) en raison de sa température trop basse.

Avec notre système à récupération multiple, la Section de séchage secondaire fournit aussi de la chaleur latente que l'on peut récupérer. Cette chaleur latente est produite par la chaleur secondaire et par le refroidissement des copeaux. À chaque étape du chauffage secondaire, une partie de la chaleur latente sert à pré-chauffer les copeaux et une autre partie monte dans les quatre divisions de la zone secondaire pour servir d'air de combustion pré-chauffé.

Supposons que la perte d'énergie dans un séchoir soit de l'ordre de 25 p. cent à chaque cycle de chauffage-séchage.

Un séchoir non régénérateur aurait une efficacité maximum E de

$$1 - 0{,}25 = 0{,}75 = E \qquad (1)$$

Avec une seule étape de récupération de la chaleur, l'efficacité devient

$$E + E^2 = 1{,}3^1 \qquad (2)$$

1.7 RÉSUMÉ À L'INTENTION DE LA DIRECTION (suite)

Quand on utilise la même énergie plusieurs fois, on a un coefficient d'efficacité de

$$E + E^2 + E^3 = +E^n = 3 \qquad (3)$$

On pourrait aussi réduire les pertes d'énergie à moins de 25 p. cent si on avait un séchoir plus gros, plus lent et mieux isolé. Toutefois, cette valeur est typique des systèmes modernes et une plus grande réduction des coûts impliquerait des investissements excessifs.

PRÉ-CHAUFFAGE ET REFROIDISSEMENT

Pré-chauffage

Quand un objet non réchauffé est séché à l'air chaud

- une grande partie de l'énergie ne sert qu'à chauffer l'objet
- le refroidissement par évaporation ralentit le processus de chauffage
- la déperdition d'eau de l'objet est ralentie par sa basse température.

Dans le cas du séchoir Intertech, une partie de l'air humide de recirculation provenant du séchage sert à chauffer les copeaux verts sans évaporation. Ainsi, on obtient un séchage primaire rapide pendant lequel l'humidité se transfère à la surface, pour le séchage secondaire.

Refroidissement

Dans le séchoir Intertech les copeaux sont refroidis graduellement par évaporation dans la zone de séchage secondaire. Cette action s'ajoute à l'effet d'évaporation causé par la chaleur secondaire.

Renouvellement de l'air dans la zone secondaire

Si l'accumulation de chaleur dans la zone secondaire s'effectuait sans contrôle, l'humidité augmenterait, et empêcherait le séchage. Afin d'empêcher un taux excessif d'humidité, la zone de séchage secondaire comporte quatre divisions dans lesquelles l'air de reprise atteint des taux d'humidité différents et les températures du point de condensation décroissent avec celle des copeaux.

L'air le plus chaud et le plus humide d'une division monte dans la suivante. La division supérieure contient l'air qui renferme le plus d'énergie. Cette partie alimente le générateur d'air chaud en air de combustion pour le séchage primaire.

1.7 RÉSUMÉ À L'INTENTION DE LA DIRECTION (suite)

Une partie de l'air de reprise de chacune des divisions passe à la zone de pré-chauffage et est remplacée par de l'air de recirculation du séchage secondaire. Par conséquent, l'air qui sort des copeaux partiellement séchés a un taux d'humidité relative élevé, mais la surchauffe ajoutée au condenseur réduit le taux à moins de 25 % pour assurer un séchage efficace.

CHAUFFAGE RÉSIDENTIEL - ÉCONOMIES

Le chauffage automatique aux copeaux secs peut réduire la facture de combustible pour une maison de la moitié aux deux tiers, selon le prix des copeaux de bois.

À Toronto, le mazout coûte 29,9 cents le litre. Pour un chauffage ayant un taux d'efficacité de 80 %, le million de kJ revient à 9,48 $.

En comparaison, les copeaux séchés au coût de 50 $ la tonne donnent 8 750 BTU par livre avec une efficacité d'environ 75 %, ce qui signifie une économie de 3,27 $ par million de kJ, voire davantage selon les prix.

Toutefois, une partie de ces économies est perdue à cause du coût de financement plus élevé du brûleur automatique de copeaux et du local à l'épreuve du feu où l'on entrepose les copeaux.

	Grosse maison	Maison moyenne	Petite maison
Consommation annuelle de mazout	2500	1500	1000
Amortissement annuel de l'installation	275	200	150
Coût total	2775	1700	1150
Consommation annuelle de copeaux	862	517	345
Amortissement annuel de l'installation (y compris la salle d'entreposage)	900	665	500
Coût total	1762	1182	845
ÉCONOMIE NETTE	1013	518	305
ÉCONOMIE EN POURCENTAGE	36%	30%	26%

1.7 RÉSUMÉ À L'INTENTION DE LA DIRECTION (suite)

La combustion des copeaux de bois

Nos calculs ont révélé que la production de copeaux de bois secs comporte de grandes variations de prix de chaque composant. Évidemment, ces variations ont une influence déterminante sur la rentabilité d'une entreprise.

On peut dire que le prix des combustibles fossiles finira par atteindre un seuil si élevé que le marché des copeaux sera viable partout où il y a des possibilités d'approvisionnement et des bâtiments à chauffer en quantité suffisante. (Ce qui est déjà le cas dans les pays scandinaves.) Si on peut acheter de la chaleur résiduelle dont la température dépasse celle du point d'ébullition de l'eau, on abaisse les coûts de quelques dollars par tonne. On peut aussi économiser environ 10 $ par tonne si on procède à partir de copeaux qui proviennent de résidus industriels plutôt que d'arbres. Au cours des premières années, quand les générateurs d'air chaud seront importés et le marché des copeaux en expansion, les fournisseurs de copeaux les mieux placés seront vraisemblablement ceux qui pourront bénéficier de coûts réduits pour la matière première ou pour l'énergie.

Les coûts, peuvent varier énormément selon les quantités produites et vendues. Une entreprise devrait avoir un marché établi pour une grande partie de sa production (disons 50 %) si elle compte atteindre le seuil de rentabilité.

Le marché des copeaux de bois

D'après notre étude, avec un coût de 50 $ et même de 75 $ la tonne de copeaux séchés, on peut réaliser des économies par rapport au mazout pour à peu près n'importe quel type de maison. Toutefois, tant que le mazout est disponible à un prix accessible, l'économie nette doit être assez importante pour vaincre l'inertie humaine. Par exemple, à peu près personne ne serait intéressé par une économie de 100 $. Par contre, dans les régions rurales et les villes où le bois constitue déjà une partie des sources de chauffage, on serait très intéressé par une économie de 1 000 $.

Les économies réalisées, tant en valeur absolue qu'en pourcentage (par rapport au chauffage au mazout) sont proportionnelles à la taille de système de chauffage. Par conséquent, le chauffage aux copeaux pourrait être très intéressant pour les petits immeubles d'appartements, de centres commerciaux, de petites usines et très grosses maisons.

1.7 RÉSUMÉ À L'INTENTION DE LA DIRECTION (suite)

ANALYSE COÛTS/BÉNÉFICES POUR UN SÉCHOIR DE COPEAUX

Coûts énergétiques

Générateur d'air chaud	750 000 kJ/h à 3,00 $ par million de kJ	= 2,25 $/h
Électricité	150 000 kJ/h à 5 cents le kWh et 36MJ/kWh	= 2,08 $/h
Coût total		= 4,37 $/h

Main d'oeuvre

Fonctionnement (2 personnes à temps partiel (qui effectuent un autre travail la plupart du temps)	= 5,00 $/h
Entretien (10 000 $ par année)	= 2,00 $/h
Coût total du fonctionnement	= 11,37 $/h
Coût de fonctionnement à 5t/h	= 2,27 $/h

Coût en capital

Un séchoir d'une capacité de 5 t/h coûte environ 155 000 $. Ce prix comprend les panneaux isolants, l'ossature d'acier, les cloisons, un gros échangeur de chaleur, un convoyeur, les ventilateurs, un générateur d'air chaud, les câbles et commandes électriques, divers dispositifs et 25 000 $ pour les imprévus.

En outre, il faut compter le prix d'un bâtiment et de l'équipement de manutention des copeaux. On ne compte pas ici les coûts de l'équipement de production des copeaux qui sont calculés dans le prix des copeaux verts. L'installation, y compris le bâtiment, coûte environ 250 000 $. On peut financer une telle somme à raison de 34 000 $ (capital et intérêt) par année pendant 20 ans.

Si on calcule 5 000 heures de fonctionnement par année, on a un coût en capital de 6,80 $/h ou 1,36 $ par tonne de copeaux.

Le coût total (fonctionnement et capital) du séchage des copeaux s'établit donc à 3,63 $/t.

1.7 RÉSUMÉ À L'INTENTION DE LA DIRECTION (suite)

Avantages du séchage des copeaux

Le séchage des copeaux donne une augmentation notable de la chaleur nette produite par tonne de solides. En outre, il permet de transformer en combustible résidentiel une matière qui ne serait autrement utilisable que pour les installations industrielles.

Un tableau produit par R.L. Stewart a été cité dans plusieurs études. Il montre l'efficacité du bois qui varie entre 77 %, à 10 % d'humidité (à l'état humide), et 58 %, à 60 % d'humidité (à l'état humide). À partir de ce tableau et d'une valeur de départ de 8 750 BTU/lb par le bois de l'écorce (à l'état sec), chaque 1 % d'humidité (à l'état sec) donne 15 BTU de chaleur disponible par livre de copeaux. En termes plus clairs, pour chaque libre d'eau que l'on extrait des copeaux, on gagne 1 500 BTU. Ce chiffre correspond aux 1 000 BTU nécessaires pour faire évaporer l'eau dans le générateur d'air chaud plus 500 pour l'air supplémentaire et la combustion incomplète qui se produit quand la fournaise se rapproche de son point d'inefficacité. Un autre avantage du séchage des copeaux est le fait que l'on peut augmenter jusqu'à 50 % la chaleur produite par une fournaise en passant des copeaux humides aux copeaux secs.

Chaleur nette tirée des copeaux humides	0.6 x 8 750 = 5 250 BTU/lb
Chaleur nette tirée des copeaux secs	0.75 x 8 750 = 6 562 BTU/lb
Gain tiré du séchage	1 312 BTU/lb x 2 204 = 2,89 MBTU/t

Notre évaluation du coût de séchage des copeaux à 2,27 $/t compte 2 700 lb d'eau pour 5 tonnes de copeaux, ou 540 lb d'eau par tonne, ou 0,245 lb d'eau par livre de copeaux. Sans séchage naturel préalable, le coût pourrait grimper à 5,00 $ par tonne, ou 5,00 $/2,99 MBTU, soit un coût de 1,73 $ par MBTU de chaleur économisée par le séchage. Ce coût est bien inférieur à celui des autres sources énergétiques.

On a mis au point un logiciel qui calcule la masse, les écoulements, la température et les enthalpies à quatre-vingt-dix endroits différents du système de séchage.

Ainsi, on pourra tirer un rendement optimal du séchoir selon les variations de température et le taux initial d'humidité des copeaux.

INTERTECH ENGINEERING CORPORATION

DESIGN OF A TREE CHIP DRYING SYSTEM

PART I OF II

FINAL REPORT

2. CORE SECTION

2.1 INTRODUCTION

As part of the Government of Canada's Alternative Energy Technology Development Programme, one of which was the substitution of forest products as an alternative fuel to oil and gas, the Intertech Engineering Corporation submitted a proposal to Energy Mines and Resources for the development of an energy efficient method of drying wet wood chips. The rationale for this work was based on the following:-

. Green chips, ie. from freshly cut live trees, are so wet that they will put out a small fire.

When they are dried barely enough to burn in a small furnace, they have disadvantages compared to dry chips:

- big variations in heat output from a given flow of chips
- excess air required for combustion
- waste of heat in vaporizing the contained water
- less reliability in conveving chips to furnace, due to thickness and greater tendency to bridging in hopper
- rotting of wet chips is a health problem
- larger furnace needed for any given heat output.

. Chips can be dried in less than one minute at a high temperature, or in between one and eight weeks at a low temperature, or at any rate between. Most existing dryers use either high temperatures or low temperatures and not the intermediate temperatures in the range between the outside air temperature and the boiling point.

. Low temperature dryers are used at present mainly for one or several individual households. To expand the scope of such a system to serve a chip merchandizing business would involve an upward scaling of everything, including space, ventilation and handling facilities. It would also require a closer control of final moisture content than where the producer and user are the same person. Low temperature dryers achieve a low energy cost by using the heat which is already present in outside air.

. High temperature dryers use waste energy at temperatures above the boiling point. Usually this involves using waste heat of another process, so there is not much incentive for using the subsequent waste heat that is at a still lower temperature.

2.1 Introduction cont.

- For users who need more dried chips than they can expect to get from a low temperature system, and who do not have an adequate source of high temperature waste heat, there is a need for an intermediate temperature dryer designed to get maximum drying out of a limited quantity of high temperature heat, supplemented by waste heat of intermediate temperature.

2.2 OBJECTIVES

(i) To design a wood chip drying system to reduce the moisture content of the chips, whereby the increase in calorific value of the chips due to moisture removal would significantly outweigh the real cost of processing.

(ii) To prove the economic design of the drying system by detailed cost estimates of the manufacture and operation of the dryer and associated components.

(iii)To determine the real cost of drying wet wood chips on a cost net unit energy delivered basis as compared to costs for wet chips, and as a function of:

- product condition
- atmosphere conditions
- operational variables
- dryer physical features
- transportation
- storage.

2.3 METHOD

Background

Ordinary energy efficiency involves many techniques for reducing various kinds of losses eg.:

- heat conduction out of the system
- high energy levels in effluents
- incomplete combustion.

Although these ordinary details will remain as important parts in any new drying system, this study is concerned specifically with a group of techniques for repeatedly reconverting latent heat back into sensible heat for drying.

The problem with latent heat recovery is that there is a continual degradation in the quality (temperature) of the heat, which rapidly reaches the point where the energy is so widely diffused that it cannot be economically re-used.

In the chip dryer described here, the air follows a generally spiral route in the opposite direction to the flow of the chips through the dryer. In each pass across the chips, the air acquires a higher moisture content, latent heat, but then it crosses a higher temperature section of the condenser, which provides superheat for further drying.

While enthalpy of the secondary air keeps rising, a smaller mass flow becomes sufficient for carrying this energy. At each zone of the secondary air recirculation, some air moves up to a higher zone and some leaves the secondary drying to go to the preheat. This transfer of energy from zone to zone provides the double benefit of supplying concentrated energy to the highest zone, the primary drying, and purging excess humidity from the lower zones where some superheat is needed.

The chips are preheated nearly to the boiling point before any drying occurs. Preheating provides faster moisture transfer within the chips and hence faster subsequent drying. It also saves primary energy by using high humidity return air from the secondary drying. The cross flow of air in the preheat section is downward to improve the drainage of water which condenses on the chips.

Heat stored in the chips during preheating will subsequently be partly recovered by evaporative cooling of the chips as they pass through areas of progressively lower temperatures and lower humidities in the secondary drying zones.

The secondary heat which is recovered from chip cooling is nearly equal to the quantity recovered from the condenser. It accounts for half of the energy supplied by the secondary zones to primary heating and to preheating.

2.3 Method cont.

So far, this energy regeneration has some of the features of a perpetual motion machine. However, some energy leaves at both ends of the system, as

- humid exhaust air at the preheating zone
- warm chips at the dry end
- hot water.

Further, a fresh input of energy is needed for upgrading the highest level of secondary energy sufficiently to provide an adequate temperature difference across the condenser. A chip-burning furnace, using top quality secondary air for combustion, provides hot gas for primary drying. Primary drying does 30% of the total drying, in addition to returning a stream of humid air at 100°C to the primary of the condenser.

The air in the primary of the condenser is of no further use for combustion. However, most of its energy is recovered by transfers in the condenser and most of the remaining energy is recovered in the preheat zone before this saturated air is finally exhausted from the dryer.

The dryer uses axial fans to retain the electro mechanical energy as heat in the system. This energy input of 150,000 kJ/h is considered as cancelling out the thermal conductivity from the system, neither of which is included in the present computer program.

Stages of Work

The work involved in this project consisted of carrying out the following tasks described as Phase I with four separate stages.

Stage 1: Review of Alternative Drying Systems

The methods of drying tree chips were analysed with respect to the following parameters:

- complexity of system
  - simple batch drying, as already tested at low temperatures
  - multiple batches with different conditions in each
  - continuous, using screw conveyors or other ways of moving chips
  - each of the above to be compared, with and without desiccant
- drying temperatures
  - effects of operation at the maximum temperature that avoids carbonizing and fire hazard

2.3 Method cont.

  - relationship of temperature to drying time and hence capacity of system
  - comparison of energy costs per unit of product for high grade energy (high temperature) and lower grade energy

- desiccants
  - how desiccants would affect the chip drying process
  - operating characteristics of various desiccants including molecular sieve, natural zeolites, silica gel
  - price & availability of desiccants, cost effectiveness
  - features of desiccant drying process
  - features of equipment used in desiccant drying

- operating analyses of various systems to dry tree chips
  - sketches of process flows
  - energy analysis, inputs and outputs
  - comparisons on estimated costs
  - evaluation of relative attractiveness based on various criteria

Stage 2: Design of Prototype System to Dry 4000 tonnes/year of Chips

- select the preferred system
- make detailed analysis of the system
- determine details of major components including:
  - type, grade, and quantity of desiccant
  - types and capacities of heaters
  - flow and pressure ratings of blowers
  - duct and valve sizes

- prepare study drawings showing:
  - general arrangement of dryer
  - general arrangement of drying system in building
  - process flow sheet
  - control schematic

Cost Predictions

- based on the details provided in Stage 2, prepare cost estimates covering:
  - initial costs
  - operating costs
  - maintenance and depreciation costs
  - cost per ton of dried chips

Natural Zeolite

- provide a section of the report showing the following details about natural zeolites:
  - physical and chemical characteristics
  - known sources including mineral deposits and suppliers
  - costs

2.3 Method cont.

Stage 3: Drawings and Specifications

- prepare manufacturing drawings of drying system
- prepare specifications
- prepare procedures

Stage 4: Characteristics, Costs, Calculations

The work to be performed in Stage 4 of Phase I shall consist of the following:

a) Verification of chip-drying characteristics by bench tests. This will include at least determinations of time/temperature/moisture relationships and confirmation of dryer size and output relationships.

b) Determination of dryer characteristics. This will include at least energy analyses and cost estimates (using, amongst others, data from Phase I, Stage 2), and a description of the effects of variations on energy needs and associated costs (using data from Phase I, Stage 1, expanded as necessary with data from other sources).

c) Estimation of costs involved in transportation storage, etc. as affected by varying fuel-moisture contents and including at least calculations of the effects of weight and volume, microbial degradation, etc.

d) Calculation of fuel burning efficiency and heating costs, including at least estimations of boiler or furnace efficiencies at varying fuel moisture contents and operating costs at varying moisture levels, calculations of effects of varying levels of water in fuel (eg. energy required to evaporate, excess air to help dry) and the impacts on furnace/boiler heating capabilities (eg. impacts of increased gas movement through heat exchangers on their ability to extract heat to transfer media), and determination of all other costs associated with varying level of moisture in fuels, including some estimate of the impacts on combuster operation of changes in fuel moisture contents from one level to another.

e) The section in the final report relevant to Stage 4 will reflect at least the above, will have as its objective the determination of the real costs of drying wood chips on a cost net unit energy delivered basis as compared to costs for wet chips. All calculations and estimates will concentrate on real conditions (eg. efficiencies of combustion equipment will be those of appliances actually or potentially in use, wood chip moisture levels will be within ranges most commonly available, etc.).

2.4 RESULTS

Results of the work are grouped under the following headings.

- Drawings - refer to Section 2.6 titled Figures and Tables which provides a full listing of all drawings produced to date. Copies of these drawings have already been forwarded to EMR. Slides are also being provided as part of this report of selected drawings.

- Transportation and Storage

  Refer to Figure No. 2.4.1 which shows that the transportation costs can range from $5/tonne to $25/tonne depending upon the method used.

  Transportation

  Transportation costs are deduced from the prices paid in the Fredericton area, where the contract price of one ton of hog fuel is $15 and persons close to the industry report that the mill gets $1 for the waste. The remaining $14, which is loosely called transportation, covers loading costs, a mileage charge, and presumably some miscellaneous costs and profit.

  These figures are close enough for evaluating the general feasibility of a dried chip business.

  Storage

  Dried chips have to be kept out of the rain but the storage does not require any heat or limitation on humidity. This is barn storage.

  By comparison with hay storage, the off-season price rises by up to $1/ton. The average cost can be reduced by shipping much of the product without any storage.

- Verification of chip drying characteristics by bench tests. This work was carried out at Queen's University under sub-contract and the results are shown in Appendix B.

- Specifications

  Manufacturing procedures and procurement specifications were prepared and have been forwarded to EMR.

- Energy and Mass Flow Rates of the Proposed Drver.

  These are included here and designated as Tables 2.4.1 for energy flow rates and 2.4.2 for mass flow rates.

2.4 Results cont.

- Determination of Dryer Characteristics

  Results of this work are given in the Appendix, Sections D.4 and D.5 titled Computer Simulation Test Results and Calculations of Dryer Performance respectively.

- Total Cost of Dried Wood Chips

  Results of these calculations in detail were included in Progress Report #5. A summary is included here as Table No. 2.4.3.

2.4 Results cont.

TABLE 2.4.1

TREE CHIP DRYER

ENERGY FLOW RATES
AT A NOMINAL OPERATING CONDITION

REFER TO DRAWING NO. IEC-TCD-FS-A-24

LOCATION	ENERGY FLOWS BTU PER HOUR			
	CHIPS	AIR	WATER	ELECTRICAL
1) INLET OF CHIPS TO DRYER	(a)	NA	97,200	NA
2) OUTLET OF CHIPS FROM DRYER	(a)	NA	112,000	NA
3) LIQUID RECOVERY FROM CONDENSER	NA	NA	65,000	NA
4) LIQUID RECOVERY FROM PREHEAT	NA	NA	51,600	NA
5) FRESH AIR INLET TO M5	NA	420,000	280,000	NA
6) OUTLET AIR FROM PREHEAT	NA	630,000	52,800	NA
7) INLET CHIPS TO FURNACE	800,000	NA	NA	NA
8) POWER TO FANS M1	NA	NA	NA	17,065
M2	NA	NA	NA	27,307
M3	NA	NA	NA	51,201
M4	NA	NA	NA	51,201
M5	NA	NA	NA	51,201
				= 197,975
9) ESTIMATED SYSTEM LOSSES				

NOTES:

(a) Each pound of water removed from the wood chips increases the calorific value of the chips on average by 1500 BTU.

∴ increase in heat content of chips is 1500 x 2600 = 390,000 BTU/hr.

(b) Total energy input to system = 800,000 + 197,975 = 997,975 BTU/hr.

(c) Ratio of energy increase to energy input = $\frac{3,900,000}{997,975} = 3.91$

2.4 Results cont.

TABLE 2.4.2

TREE CHIP DRYER

MASS FLOW RATES FOR AIR AND WATER AT A NOMINAL OPERATING CONDITION

REFER TO DRAWING NO. IEC-TCD-FS-A-24

LOCATION	MASS FLOWS POUND PER HOUR	
	WATER	DRY AIR
1) INLET OF CHIPS TO DRYER	5400	NA
2) OUTLET OF CHIPS FROM DRYER	2800	NA
3) LIQUID RECOVERY FROM CONDENSER	990	NA
4) LIQUID RECOVERY FROM PREHEAT	1200	NA
5) FRESH AIR INLET TO M5	270	35,000
6) OUTLET AIR FROM PREHEAT	680 *	35,000

* Vapour

NOTES:

(a) Flow rate of anhydrous wood chips ....6600 pounds per hour
(b) Specific heat of anhydrous wood chips.......0.6
(c) Inlet temperature of wood chips.........50°F
(d) Outlet temperature of wood chips........72°F
(e) Heat loss of chips = (22x0.6x6600)+(22x1.0x3070) = 154,660
(f) Temperature of condensate at location (3)......115°F, BTU/hr.
(g) Heat loss of condensate at location (3)......65,000 BTU/hr.
(h) Temperature of inlet air at location (5)........50°F
(i) Temperature of air leaving preheat (Loc.6)......77°F
(j) Temperature of air inlet to furnace (Loc.7)....195°F
(k) Flow rate of wood chips to furnace (Loc.7)..150 pounds per hour

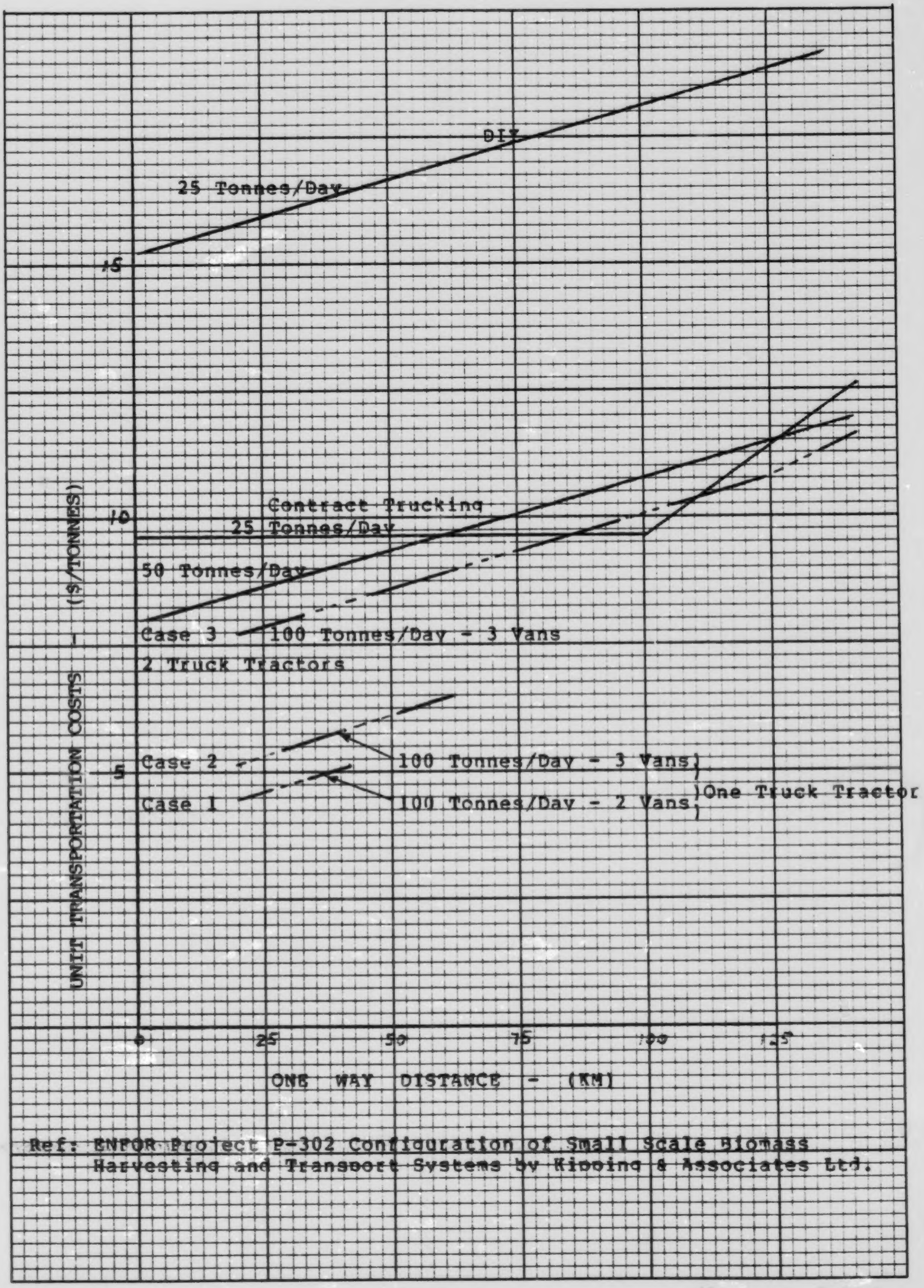
2.4 Results cont.

TABLE 2.4.3

TOTAL COST OF DRIED CHIPS, DELIVERED

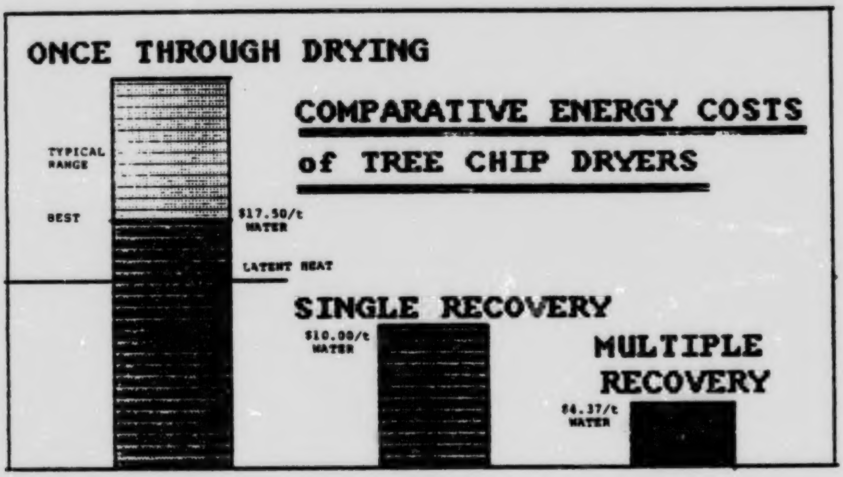
	Most Favourable Costs	Median Costs	Least Favourable Costs
GREEN CHIPS, PER TON			
Royalty	0	1.00	2.00
Chipping	5.00	7.50	10.00
Del. to Dryer	10.00	12.00	14.00
Stge. at Dryer	0	.50	1.00
SUBTOTAL	15.00	21.00	27.00
DRYER, PER HOUR			
Heat	0	5.00	7.50
Electricity	2.08	2.08	2.08
Op. Labour	5.00	10.00	20.00
SUBTOTAL	7.08	17.08	29.58
Tons dried chips/hr	5	4	3
Op.Cost/ton	1.42	4.27	9.86
CAPITAL COSTS			
Complete Drying Plant	150,000	200,000	250,000
Operating Life, years	25	15	10
Straight line depn.	6,000	13,333	25,000
Yrly maint. %	.08	.10	.12
Amount	12,000	20,000	30,000
Yrly Cap. & Maint.	18,000	33,337	55,000
Op.Hrs/yr	5,000	2,500	1,500
Cap.& Maint/hr	3.60	13.33	36.67
Cap. & Maint/ton	.72	3.33	12.22
Tot.Cost/Ton FOB	17.14	28.60	49.08
Retail delivery cost	12	15	18
	-------	-------	------
COST DELIVERED	29.14	43.60	67.08

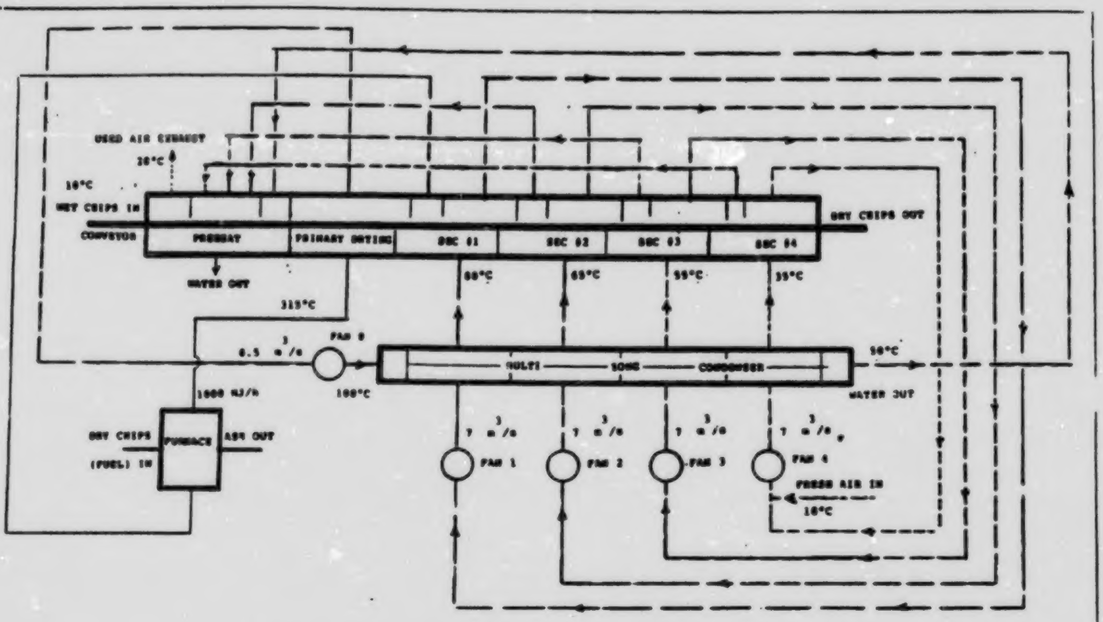
TREE CHIP TRANSPORT COSTS



Ref: ENFOR Project P-302 Configuration of Small Scale Biomass Harvesting and Transport Systems by Kipping & Associates Ltd.

GRAPHIC CONTROLS CANADA LTD.
MADE IN CANADA
G-5 SQUARE 10 X 10 TO THE INCH




USED AIR EXHAUST
20°C
10°C
WET CHIPS IN
CONVEYOR
PREHEAT
PRIMARY DRYING
SEC #1
SEC #2
SEC #3
SEC #4
DRY CHIPS OUT
WATER OUT
315°C
80°C
65°C
55°C
35°C
FAN 0
6.5 m³/s
100°C
1000 MJ/h
MULTI ZONE CONDENSER
50°C
WATER OUT
7 m³/s
7 m³/s
7 m³/s
7 m³/s
FAN 1
FAN 2
FAN 3
FAN 4
FRESH AIR IN
10°C
DRY CHIPS (FUEL) IN
FURNACE
ASH OUT

EMR - IEC TREE CHIP DRYING SYSTEM
(with heat recovery)

2.5 DISCUSSIONS

Regenerative Drying

The remarks which follow concern the characteristics of heat recovery sub systems within a drying system. The heat recovery features include:

- condensing of vapour in a preheat zone
- condensing of vapour in a heat exchanger for secondary drying.

The comments discuss individual features of dryers. as revealed by a computer model.

Effective heat recovery in this kind of dryer is real. The computer program clarifies a number of features which were previously understood in a fuzzy way. These are:

Performance of the condenser is heavily dependent upon having a large temperature difference between the primary and the secondary. This problem shows itself mainly at both ends of the secondary drying process.

At the high end, zone sec #1, it was obvious in early runs of the computer program, that there was not enough temperature difference between primary and secondary to produce a worthwhile heat recovery.

The total quantity of evaporation was not reduced at all by the subsequent elimination of the condenser section in sec #1.

At the low end of the secondary drying, in sec #4, the temperature in the saturated primary air drops from 152°F to as low as 132°F in passing through this zone. This low primary temperature reduces the average temperature difference between primary and secondary to 58°F. which is much lower than we hoped for.

Even at 132°, this air leaving the condenser primary is still the second highest grade of heat available for the preheat. It is at a temperature where a slight increase in temperature would be very welcome. This can be done by a reduction in the condenser capacity.

The first cooldown zone which follows immediately after the primary drying, separates the air into streams at widely different temperatures. Our aim in splitting this into two separate zones. with individual fans, is for the purpose of raising the top temperatures of both the air moving up to the primary

2.5 Discussions cont.

zone and the air going into the top preheat. It is hoped that the second cooling zone will also produce a higher temperature for preheat air, higher than the temperature of the condenser primary exhaust.

By eliminating the condenser from sec #4, the lowest end drying zone, there will be a nearly complete elimination of the heat loss (of up to 400,000 btu/h) associated with the warm product which leaves the system at 20° to 30° above ambient. This cooldown section will deliver air to zone #3 at a moderately higher enthalpy than the 20 btu/lb of ambient air, to start the buildup towards high energy primary air. Some air will be exhausted directly from this zone, because its temperature is below the temperature of the preheat exhaust.

The kind of dryer needed for the features discussed above is basically the same as the one we planned a few months ago. The difference is a smaller condenser, smaller fans and fewer preheat ducts. Construction cost will be reduced by 25%.

Condenser Capacity

Here are the conclusions from a series of runs, using variable condenser capacities from 12,000 btu/h/°F down to 0 btu/h/°F.

1. The condenser demonstrates the law of diminishing returns.

2. Aside from these results, the condenser is a relatively costly component.

3. In view of 1 and 2 above, a smaller condenser looks best. Presently, I would say, use C = 5000 btu/lb/° in the present design which uses 3 stages of condensing, with none in sec #1.

4. The detailed results on the screen showed that secondary temperatures are lower than were expected based on manual calculations. The faster iterations on a computer allowed greater variations in all the constants and variables, and we found that a relatively large flow rate through the primary system produced maximum evaporation.

However, these lower secondary temperatures will require a longer drying time, probably by using a deeper bed of chips on the dryer.

2.5 Discussions cont.

The remarks above were written on March 12. By March 15, the program was further revised to show the condenser used in zone sec #3 only, with recirculating cooling in zones 1 & 2, and once through cooling in zone 4. This improved the temperature drop at the condenser, resulting in a total evaporation of 2600 lb water/h while using a total condenser capacity of 10,000 btu/h/°F. This compares with an originally planned condenser capacity of 4 x 8000 btu/h/°F.

The computer program does not consider this because time is not one of its parameters, except where various numbers are stated on a per hour basis.

During development of the program the computer ran out of memory many times, making it necessary to eliminate:

- explanatory notes on the program lines
- a fully detailed printout of results
- some extreme high or low values on the psychrometric tables.

Consequently, manual calculations would be necessary to explore the full consequences of running with secondary temperatures that are lower than previously hoped. This will result in a longer drying time but the savings on condenser cost and smaller blowers will reduce the total cost of the dryer by about 25%. The higher fan pressures associated with deeper beds will be compensated for by having generally smaller required flow rates.

2.5 Discussions cont.

Heat from Combustion of Wood Chips
from chart by R.L. Stewart based on 8750 btu/lb of solids

Moisture % wet basis	Boiler Effic. %	Btu per lb. solids	Lb.water per lb. solids	Water Removal/ lb.solids	Diff. in Btu/lb	Gain/ lb.water removal
60	58	5075	1.50			
				-.50	437	874
50	63	5512	1.00			
				.33	525	1591
40	69	6037	.67			
				.24	350	1458
30	73	6387	.43			
				.08	263	1461
20	76	6650	.25			

Since water contents above 50% are not burnable at all in domestic furnaces, use the three lower figures, which show an average heat gain of 1500 Btu for each lb. of water removed from the chips.

The regenerative dryer removes 2600 btu/h at an energy cost of 1,000,000 btu/h, or an energy cost of 385 btu/lb water. Thus each expenditure of 385 btu for drying produces an increase of 1500 btu in furnace heat, for an overall c.o.p. of 3.9.

2.6 FIGURES & TABLES

TREE CHIP DRYER DRAWINGS LIST

IEC-TCD-FS-C-01	PROCESS/ENERGY FLOW DIAGRAM		86/09/25
		Rev.1	86/10/01
		Rev.2	86/11/19
IEC-TCD-GA-D-02	GENERAL ARRANGEMENT SECTIONS		86/10/01
		Rev.1	86/11/28
IEC-TCD-GA-D-03	GENERAL ARRANGEMENT SECTIONS		86/10/02
		Rev.1	86/11/28
IEC-TCD-EC-C-04 (Superceded - See Dwg. - 19)	ELECTRICAL/CONTROL DIAGRAM		86/10/02
IEC-TCD-SK-A-05	ALUMINUM FIN TUBE SKETCH		
IEC-TCD-SK-D-06	SKETCHES FOR TRAY TYPE CONVEYOR		86/10/15
IEC-TCD-SK-D-07	SKETCHES FOR WIRE MESH BELT CONVEYOR		86/10/16
IEC-TCD-SK-D-08	SKETCHES FOR RECIPROCATING MULTIPLE WEDGE CONVEYOR		86/10/17
IEC-TCD-GA-D-09	GENERAL ARRANGEMENT OF HEAT EXCHANGER/CONDENSER		86/10/20
IEC-TCD-GA-D-10	GENERAL ARRANGEMENT OF SHEET METAL INTERNAL PARTITIONS		86/10/23
IEC-TCD-GA-D-11	GENERAL ARRANGEMENT OF INSULATED CASING PANELS		86/10/25
IEC-TCD-DD-D-12	INSULATED PANEL DETAILS		86/10/28
IEC-TCD-DD-D-13	DETAILS OF INSULATED ACCESS DOORS		86/10/29
IEC-TCD-GA-D-14	GENERAL ARRANGEMENT & DETAILS OF PARTITION BETWEEN CONVEYOR & HEAT EXCHANGER & FAN SUPPORTS		86/10/30
IEC-TCD-GA-D-15	GENERAL ARRANGEMENT OF STEELWORK - PLAN & ELEVATION		86/10/31
IEC-TCD-GA-D-16	GENERAL ARRANGEMENT OF STEELWORK - SECTIONS & DETAILS		86/11/03

2.6 Figures & Tables/Drawings List cont.

IEC-TCD-GA-D-17	ARRANGEMENT & DETAILS OF FEEDER HOPPER AT ENTRY TO DRYER	86/11/06
IEC-TCD-GA-D-18	ARRANGEMENT & DETAILS OF DRYER DISCHARGE END CHUTE	86/11/06
IEC-TCD-EC-D-19	POWER AND CONTROL WIRING SCHEMATIC	86/11/28
IEC-TCD-SD-D-20	ASSEMBLY INSPECTION TESTING AND COMMISSIONING PLAN	86/11/26
IEC-TCD-GA-D-22	ARRANGEMENT & DETAILS OF INTERNAL DUCTING	86/11/20

INTERTECH ENGINEERING CORPORATION

DESIGN OF A TREE CHIP DRYING SYSTEM

PART I OF II

FINAL REPORT

3. FINAL SECTION

2.6 Figures & Tables/ Drawings List cont.

IEC-TCD-SK-A-05 ALUMINUM FIN TUBE SKETCH

This A size sketch shows a short section of tube and gives the parameters for forming the integral fin.

IEC-TCD-SK-D-06 SKETCHES FOR TRAY TYPE CONVEYOR

This D size sketch shows a possible method of transporting the chips through the dryer by means of a series of perforated trays hinged and connected together to form a chain.

IEC-TCD-SK-D-07 SKETCHES FOR WIRE MESH BELT CONVEYOR

This D size sketch shows a possible method of transporting the chips through the dryer by means of a woven wire mesh belt driven by rubber covered drums and supported on idler rollers.

IEC-TCD-SK-D-08 SKETCHES FOR RECIPROCATING MULTIPLE WEDGE CONVEYOR

This D size sketch shows a possible method of transporting the chips through the dryer by means of horizontal perforated wedges connected to a central spine which pushes them forward then backwards over a perforated deck.

IEC-TCD-GA-D-09 GENERAL ARRANGEMENT OF HEAT EXCHANGER/CONDENSER

This drawing shows the housing for the finned aluminium tubes for the heat exchanger/condenser section of the dryer.

IEC-TCD-GA-D-10 GENERAL ARRANGEMENT OF SHEET METAL INTERNAL PARTITIONS

These partitions divide the dryer into the various temperature zones required.

IEC-TCD-GA-D-11 GENERAL ARRANGEMENT OF INSULATED CASING PANELS

This drawing shows the assembly of panels that make up the exterior of the dryer unit.

IEC-TCD-DD-D-12 INSULATED PANEL DETAILS

This drawing shows the construction details for the individual panels.

2.6 Figures & Tables/Drawings List cont.

IEC-TCD-DD-D-13	DETAILS OF INSULATED ACCESS DOORS

This drawing shows the construction details of the external access doors.

IEC-TCD-GA-D-14	GENERAL ARRANGEMENT & DETAILS OF PARTITION BETWEEN CONVEYOR & HEAT EXCHANGER & FAN SUPPORTS
IEC-TCD-GA-D-15	GENERAL ARRANGEMENT OF STEELWORK - PLAN & ELEVATION
IEC-TCD-GA-D-16	GENERAL ARRANGEMENT OF STEELWORK - SECTIONS & DETAILS
IEC-TCD-GA-D-17	ARRANGEMENT & DETAILS OF FEEDER HOPPER AT ENTRY TO DRYER
IEC-TCD-GA-D-18	ARRANGEMENT & DETAILS OF DRYER DISCHARGE END CHUTE

3.1 CONCLUSIONS

- In the specific case of wood chips, it has been demonstrated by design and calculations that the total energy required to remove one pound of water from wet chips with a moisture content ranging from 50 percent to 25 percent is in the range of 350 BTU.

- The technique of multiple recovery of vapour energy from wood chips in the drying system designed in this project, can reduce energy consumption by a factor of four compared to single pass drying systems.

- The fuel cost of residential heating using dried wood chips can be reduced from one half to two thirds compared to heating with oil depending on the size of residence.

- A medium temperature, atmospheric dryer of the regenerative type with multi stage condenser recovery with a tube in shell arrangement and a nominal rating of 2000 pounds per hour of water removal from wood chips, can be built and operated with a coefficient of performance (COP) ratio of between four and five.

- The capital cost of a dryer based on drawings which were prepared from calculations of energy and mass transfers and balances in a design having a nominal water removal capacity of 2000 pounds per hour has been estimated at C$155,000 exclusive of foundations, and transport of the chips to the site.

- The operating cost of a dryer with a nominal rating of 5.5 tonnes of 50 percent moisture wood chips is approximately C$7.00 per hour for labour and energy only.

- Where the capital and operating costs of a particular drying system have become firm, the unit cost for dried chips remain highly dependent upon the hourly production rate and the number of operating hours per year.

- Based on average capital and operating costs shown above, variations of from three to five tonnes per hour of dried chips can vary the delivery cost of the chips to between C$33 and C$58 per tonne.

- Presently the computer simulation of economic factors considers only the effect of changes in details of the dryer and the mass and energy flows. This information could be fed into a spreadsheet programme to optimize the cost variables for specific situations.

- Transportation costs of chips can range from $5/tonne to $25/tonne depending upon the method.

3.1 Conclusions cont.

- Laboratory tests of chip drying at air temperatures from 75°C to 125°C showed that both softwood and hardwood chips can have their moisture content reduced by one half in four to twelve minutes.
- The net energy input required for drying is reduced from over 3000 kJ/kg (1300 BTU/lb water) to 1160 kJ/kg (500 BTU/lb water) by converting some of the water vapour back into sensible heat in the condenser, by using waste heat to preheat the chips, and by using some evaporative cooling in the secondary drying sections.
- Chips can be dried in less than one minute at a high temperature, or in between one and eight weeks at a low temperature, or at any rate between. Most existing dryers use either high temperatures or low temperatures and not the intermediate temperatures in the range between the outside air temperature and the boiling point.
- The key principle of the Intertech Dryer is that it condenses a large proportion of the vapour evaporated from the chips, thus supplying intermediate temperature heat for further drying. When a high temperature air stream is passed through a wet product, evaporation cools the air but does not reduce its energy: the energy is still there, but as vapour, which is less useful than high temperature energy. In the Intertech Dryer, the condenser supplies intermediate temperature heat and changes vapour back into a liquid. The intermediate heat does half of the required drying.
- Desiccant dehumidification produces a low absolute humidity combined with a high temperature.

  This is a good condition for drying of solids, but is not optimal. Its emphasis on a low humidity is needed only when a very dry condition is required. For bulk drying, as in the case of the chip dryers, a higher temperature is the key condition rather than a low absolute humidity. Each 10°C of temperature increase drops the relative humidity by half and speeds the molecular motion for a faster drying rate.
- Small samples of softwood chips and hardwood chips were dried in laboratory tests conducted under the supervision of Prof. H.A. Becker at Queen's University. A separate report on these tests is appended to this report.

3.1 Conclusions cont.

These tests show that the drying time for a 50% reduction in the moisture content of the chips varies from 4 minutes in an air temperature of 125°C to 12 minutes at an air temperature of 75°C. For optimizing the performance of the planned dryer, drying time can be altered by varying both the speed of the conveyor and the thickness of the chip bed, to provide the exact amount of drying needed.

- Dried chips have to be kept out of the rain but the storage does not require any heat or limitation on humidity. This is barn storage.
- One ton of dried chips provides the energy equivalent of 450 litres of oil, which costs 26.4 cents/l, total $118.80. Projected delivered costs of between $50 and $60 per ton of chips provide a saving of between $500 and $1000 per year for each household which switches to tree chips.
- By re-using some of its own waste heat for preheating and for part of the drying, the Intertech Dryer has a lower net consumption of energy than other thermal dryers. When other types of dryers are able to use free energy this diminishes the importance of energy recovery but even the Intertech Dryer has the potential for using waste heat from another process.
- Chip Handling Tests
    - gravity flow on a sloped surface is too variable to be used as part of a process
    - horizontal pushed flow is acceptable and presents no serious problems
    - upward sloped push flow produces uneven height in the pile. For upward slopes a moving belt is needed
    - flow between parallel surfaces is difficult and should be avoided.

3.2 RECOMMENDATIONS

This project has been a technical success story.

The design and calculations have shown that the energy needed for water removal in tree chips can be reduced by a factor of four or more compared to existing once through type dryers. The key to this reduction is the use of a multi staged condenser which in turn allows the chips to be dried into a residential fuel which is economically superior to coal.

The drying system designed here meets the technical requirements of the Government of Canada's Guidelines on renewable. alternative energies for heating.

With the foregoing in view the following recommendations are made for action by both Intertech Engineering and the Department of Energy Mines and Resources.

- Intertech Engineering should pursue the marketing and commercialization aspects of drying wet tree chips in order to capitalize on this unique design process for energy conservation.
- The tree chip dryer which has evolved during the course of this EMR funded project is both unique and technically superior to presently used methods. As such the concept of energy efficient drying by the use of multi stage (regenerative) recovery of heat, by condensing a large proportion of the vapour evaporated from the chips and thus supplying intermediate temperature heat for further drying and preheating should be patented.
- Intertech Engineering and EMR should pursue further applications of the principle of energy efficient drying which was developed in this project. Preliminary studies have shown that fuel grade peat can have its calorific value increased two fold and made into a fuel which is an economic alternative to coal provided the water removal from products can be carried out in a much more energy efficient manner than presently employed. As such the application of the technique developed here should be expanded.

3.3 REFERENCES & BIBLIOGRAPHY

"Wood Chip Fuel for Residential Use", by Island Energy Associates, Nov. 1981.

"Implementation Planning for Wood Energy in Prince Edward Island", by C. Kirk Brown & Andrew B. Wells, of Institute of Man & Resources, Jan. 1983.

"Survey of Wood Fuel Use in Prince Edward Island 1982-1983", by C. Kirk Brown & others, for Prince Edward Island Energy Corporation.

"Wood Chip Drying Seminar", Proceedings compiled by E.T. Owens, of Research & Productivity Council, Fredericton, New Brunswick, Nov. 1986.

"A State of the Art Study of Residential Wood Chip Heating Systems", by D. Murray, for Energy Mines & Resources. Canada, March 1986.

"Factors Affecting the Occurrence of Fungi in Fuel Chips for Domestic Consumption", by Thomas Thornquist and Hans Lundstrom of The Swedish University of Agricultural Sciences, 1980.

"Fungi on Fuel Wood Chips in a Home", by J. David Miller and others, of University of New Brunswick, Jan. 1981.

"Small Scale Wood Chip Fuel Harvesting and Processing", by M. H. Schneider and others, of University of New Brunswick, Feb. 1985.

"Guide and Data Book", by American Society of Heating, Refrigerating and Air Conditioning Engineers, 1966 edition.

"An Overview of Achievements in Bioenergy Research, Development and Demonstration", by Passmore Associates International and Ensyn Engineering, Feb. 1987.

"The Economics of Integrated Full Tree Harvesting and Central Processing in Jack Pine", by Pierre Zundel, June 1986.

3.4 APPENDICES

APPENDIX A

CONTRACT DIRECTORY INFORMATION

TITLE: DESIGN OF A TREE CHIP DRYING SYSTEM

CONTRACTOR:	SCIENTIFIC AUTHORITY:
Intertech Engineering Corporation 199 Bay Street, Suite 503 Toronto, Canada, M5J 1L4	Dr. W.E. Lowe Renewable Energy Division Dept. of Energy, Mines & Resources 460 O'Connor Street Ottawa, Ontario, K1A 0E4
PRINCIPAL INVESTIGATOR:	CONTRACT NO:
John Craig Cringan (416)366-2135	DSS File No.51SZ.23216-6-6177
DURATION:	COST:
Commencement 86-07-17 Delivery Date 87-03-31	Fiscal Year 1986 - $88,838.00

OBJECTIVES:

- Determination of the real costs of drying wood chips on a cost net unit energy delivered basis as compared to costs for wet chips, and as a function of product flow rate; moisture content; temperature of drying; and flow rate of air.
- Determination of the drying characteristics of a dryer in terms of energy required to remove a pound of water at varying operating conditions of the dryer and product.
- Selection and design of a drying system for wood chips which gives the lowest cost per tonne of dried product.

Appendix A - Contract Directory Information cont.

RESULTS:

A study was completed on various types of dryers for tree chips in order to select and carry-out a detailed design of the most economically efficient dryer to incorporate in a chip drying system. The selected dryer is described as a medium temperature, regenerative type, with heat recovery via a tube in shell heat exchanger. The dryer has a nominal rating of 2000 pounds of water removal per hour with a net energy input of less than 1160 kJ/kg (500 BTU/pound). Detailed manufacturing drawings, procedures and specifications were prepared.

CONCLUSIONS:

A dryer for wood chips can be built for operation on a continuous basis at medium conditions of temperature and atmospheric pressure and at a lower total cost than high temperature or ambient temperature dryers.

The dryer can be optimized for varying moisture conditions of the product to produce chips with a constant moisture content of 25 percent.

With the design of dryer selected in this work, tree chips can be dried within the normal operating conditions by supplying less than 500 BTU of heat energy per pound of water removed from the chips. This is substantially less than alternative designs investigated.

RECOMMENDATIONS:

The use of latent heat for drying and preheating and the partial cooldown of the tree chips to achieve drying that recovers the energy of preheating, are features which distinguish this dryer from other thermal dryers and makes it very energy efficient. As a consequence this design of drying could become a standard in the future and so further development for other solid fuels should be investigated.

APPENDIX B

QUEEN'S UNIVERSITY REPORT
ON
BENCH TESTS ON THE DRYING OF TREE CHIPS

(CONSISTING OF 56 UNNUMBERED PAGES)

BENCH TESTS ON THE DRYING OF TREE CHIPS

H.A. Becker[a] and M. Leboldus[b]

Department of Chemical Engineering
Queen's University at Kingston
Kingston, Canada K7L 3N6

Final Report on a study performed under contract for Intertech Engineering Corporation, 199 Bay Street, Suite 503, Toronto, Canada M5J 1L4

November, 1986

---

[a] Professor and Head of Department

[b] Graduate student, M.Sc. program

Abstract

Drying of fixed beds of spruce and maple tree chips in fixed beds about 75 mm deep has been investigated. The inlet temperature of the drying air was 75, 90, 100 and 125 °C and the superficial velocity was 0.5 m/s. Two inlet humidity conditions were used, one with dry air and the other with air that was saturated with water vapour at 50 °C before being heated to the operating level. The initial moisture content of the chips was desired to be about 50% w.b. but was in fact 32--40 % w.b. Drying rate under these conditions was found to be effectively controlled by the energy budget, part of the energy being usefully employed in evaporating moisture and the remainder being lost in heating the bed and convection away in the leaving air. Drying efficiencies were typically high, with exit air temperatures dropping close to the wet-bulb temperature of the inlet air.

Notation

a	coefficient in initial linear drying laws (5) and (13)
A	cross-sectional area of bed, m^2
b	coefficient in initial linear drying laws (5) and (13), s^{-1}
c_{pa}	heat capacity of air, J/kg °C
c_{pd}	heat capacity of wood dry matter, J/kg °C
c_{pv}	heat capacity of water vapour, J/kg °C
G_1	$= \rho_1 U_1$, inlet mass velocity of air, kg/m^2s
L	length of a tree chip (Fig. 5), m
m	mass of bed of chips at time t or, in drying of single chips, mass of chip, kg
m_o	initial value of m, kg
m_d	dry mass of bed of chips or, in drying single chips, dry mass of single chip, kg
m''_d	$= m_d/A$, dry mass of bed per unit bed area, kg/m^2, the "bed loading"
$\dot{m}_1$	$= \rho_1 U_1 A_1$, inlet mass flowrate of air, kg/s
P	length of cut face of the chip (Fig. 5), m
T	thickness of tree chip (Fig. 5), m
T	temperature, °C
T_a	ambient air temperature, °C
T_b	sand-bath temperature, °C
T_o	initial temperature of chips, °C
T_s	adiabatic saturation or (effectively) wet-bulb temperature of air entering bed, °C

T_1	temperature of air at bed inlet, °C
T_2	temperature of air at bed outlet, °C
t	time, s
U_1	$= \dot{m}_1/\rho_1 A$, superficial velocity of air entering bed, m/s
V	volume of chip (Fig. 5), m^3
W	mean moisture content d.b. of drying bed at time t or, in drying single chips, of a chip, kg/kg
W_o	initial value of W
w	mean moisture content w.b. of drying bed at time t or, in drying single chips, of a chip, kg/kg
w_o	initial value of w
α	cutting angle of chipper (Fig. 5)
Δh_v	specific enthalpy of vapourization of water, J/kg
η_t	thermal drying efficiency, eq. (7)
η_p	psychrometric drying efficiency, eq. (8)
η_{to}	initial value of η_t, eq. (11)
η_{po}	initial value of η_p, eq. (12)
$\bar{\eta}_t$	integral thermal drying efficiency, eq. (16)
$\bar{\eta}_p$	integral psychrometric drying efficiency, eq. (17)
ρ_1	density of air at dryer inlet, kg/m^3

1. Introduction

This study was done under contract for Intertech Engineering Corporation. The firm is developing an energy-efficient system for hot-air drying of tree chips. Experimental data were wanted to guide the dryer design. The tests were to be done on a fixed-bed batch dryer. The results would apply not only to this mode of operation but also to the continuous, cross-flow, moving-bed dryers of actual interest. In this report, the experiments are described, the data are presented, and an analysis of the data is given. The analysis provides both a critical examination of the results and a generalized interpretation that will serve as a basis for applications to dryer design and prediction of performance.

2. The experiments

2.1 Fluidized bed sand bath experiment

A fluidized bed sand bath (Fisher constant-temperature bath) was used to study the drying of single wood chips in dry air in a strongly constant-temperature environment. Heat transfer to the drying particle here is more efficient than in any other medium. The results define an upper limit to the practically attainable drying rate in drying with air at atmospheric pressure.

A weight was hung on the test chip to keep it immersed in the bed. The chip was periodically removed and weighed, then quickly returned to the bath. Drying time was measured as the cumulative exposure time in the bath. This procedure is not the best but was adopted because of shortage of time. Ideally, a large number of particles should be used at each test condition, each being exposed for a different time and then discarded. The intermittent upsets caused by withdrawal from the bath, weighing and returning are eliminated in this method.

2.2 Fixed-bed air dryer

The fixed-bed dryer system is shown schematically in Fig. 1 and in photographs in Figs. 2, 3 and 4. The drying chamber is cylindrical, 100 mm dia, with a wire mesh bed support. The bed of wood chips was placed in a wire mesh cup, Fig. 4, which fitted closely inside the drying chamber. This allowed quick removal of the bed for periodic weighing and subsequent return. Weighing was done with a very fast automatic electronic digital balance. The interruption of exposure for each weighing was no more than 20 s. So long as time interruptions are short relative to the exposure period in between, the error introduced is negligible. The drying time is the cumulative exposure time.

The drying air was electrically heated. In some experiments it was humidified by bubbling it from a sparger through a pool of water 0.7 m deep, contained in a barrel and maintained at 50 °C. The air may be assumed to have been warmed to and saturated at 50 °C. The air then passed on to the heater section and the drying bed.

Thermocouples were used to measure air temperature at bed entrance and exit.

The air supply system was calibrated so that the regulated supply pressure was correlated with the flowrate.

2.3 Materials

Spruce chips and maple chips were obtained through contacts at the University of New Brunswick (Professor Picot in Chemical Engineering and Professor Schneider in Wood Science and Technology). The spruce chips were received virtually as produced from green trees and required no conditioning. The maple chips, however, were quite dry and were therefore rewetted by liquid water addition. All samples were held in storage in a cold room to retard spoilage.

2.4 Moisture determination

Samples for moisture determination were ground in a Wiley mill. Moistures were then determined by the one-hour, 130 °C air-oven method. Ground samples were held in standard aluminum weighing dishes with covers (a type prescribed for use in determining moisture content of cereal grains).

2.5 Operating conditions for the fixed-bed drying experiments

The operating conditions were as specified in the contract and in discussions with Claude Burrell of Intertech Engineering Corp. and are summarized in Table 1. Runs were carried out in duplicate (two at each operating condition).

3. Results

3.1 Chip size and shape

The chips may be characterized as approximately rhombohedral and plate-like, Fig. 5, of length L on the faces parallel to the grain, of width W across the grain, and of thickness T. The cutting angle α was about 60°. The chip volume approximates $V = LWT$.

Table 21 of Appendix A shows measurements of 25 spruce chips. The mean dimensions are $L = 24$ mm, $W = 13$ mm, and $T = 3.6$ mm.

Table 22 of Appendix A shows data on 25 maple chips. These averaged $L = 10$ mm, $W = 12$ mm, and $T = 2.5$ mm.

The inequality in size of the spruce and maple chips makes direct comparison of drying rates questionable. However, these were the materials with which we were supplied by our sources in New Brunswick and, lacking a local capacity for making chips, we had to work with them in order to complete the work in the available time.

3.2 Bed moisture content vs. time: the data

Denote by w the mean moisture content w.b. (wet basis) of the drying bed at time t. It is basically a fraction (rather than a percentage), and is in fact the mean mass fraction of moisture in the bed. We have

$$w = (m - m_d)/m \ , \qquad (1)$$

where m is the mass of the bed at time t and m_d is the dry mass. When dry air is used, m_d is the mass of the bed at infinite drying time.

The moisture content of wood and many natural products in commerce is usually specified on wet basis. However, some aspects of drying calculations are more easily done on dry basis. Denote by W the mean moisture content d.b. (dry basis) of the bed at time t. We have

$$W = (m - m_d)/m_d \qquad (2)$$

This is an example of the measure of composition known as mass ratio. It is related to the mass fraction moisture or moisture content w.b. by

$$W = w/1 - w, \tag{3}$$

$$w = W/(1 + W) \tag{4}$$

The raw data from our study of fixed-bed drying of tree chips are records of mean bed moisture content, w or W, as a function of time. The data are tabulated in Appendix A and also displayed graphically on semi-logarithmic paper. The semi-logarithmic representation does not necessarily have any theoretical significance but has the virtue of displaying the data with equal accuracy over the whole range.

3.3 An empirical drying law

An equation representing the function w(t) or W(t) is commonly called a drying law. We have examined the data for any regularity of behaviour expressible in a simple drying law. In practice, initial moisture contents of freshly cut green-wood chips are around 50 % w.b. and final moisture contents after drying, acceptable for storage, around 25 % w.b. Thus practical interest tends to be concentrated in the range $w/w_o = 0.5$--1. The data, Figs. 6--9, in this range are well represented by

$$w/w_o = a - bt \qquad (5)$$

where a = 1 for the drying of spruce chips with dry or humid air, 1.015 for maple chips with dry air, and 1.06 for maple chips with humid air (the humid air, as explained in Sect. 2.2, was saturated at 50 °C). The coefficient b, Fig. 10, is strongly correlated with the dryer inlet air temperature T_1.

3.4 The drying efficiency

Figures 6--10 give indications that diffusion of moisture within chips may be the rate-controlling factor in drying. This mechanism is not, however, borne out by closer analysis of the results. Heat and mass transfer between chips and air are not very critical either. The process is in fact effectively regulated by the energy budget. It may be argued that if air that is taken from the atmosphere at temperature T_a and heated to temperature T_1 is supplied to the bed at mass flowrate $\dot{m}_1$, kg/s, then heat is supplied for the process at rate $\dot{m}_1 c_{pa} (T_1 - T_a)$, W. A part of this heat, in quantity

$$-(\Delta h_v)dm/dt = -(\Delta h_v)m_d \, dW/dt,$$

is used for evaporating moisture, part is used to change the temperature of the bed, and the remaining part, closely approximating $\dot{m}_1 c_{pa}(T_2 - T_a)$, escapes with the departing air. We may thus write

$$-(\Delta h_v)dm/dt = \eta_t\ \dot{m}_1 c_{pa}(T_1 - T_a), \tag{6}$$

where $\eta_t(t)$ is the instantaneous efficiency of drying. To put the result on a general basis, independent of the bed cross-sectional area A, we reformulate it as

$$-(\Delta h_v)m_d''\ dW/dt = \eta_t\ G_1 c_{pa}(T_1 - T_a), \tag{7}$$

where

$m_d'' = m_d/A$ = bed loading, the mass of wood dry matter per unit bed area, kg/m²

$G_1 = \rho_1 U_1 = m_1/A$ = mass air flow to bed per unit bed area, kg/m²s

The usefulness of air for vapourizing moisture has a theoretical limit that is reached when it is cooled to the wet-bulb temperature relative to its state at the dryer inlet. This suggests another efficiency concept which we will call the psychrometric drying efficiency and denote by η_p:

$$-(\Delta h_v)m_d''\ dW/dt = \eta_p\ G_1 c_{pa}(T_1 - T_s), \tag{8}$$

where T_s is the aforesaid saturation or inlet wet-bulb temperature.

Equations (7) and (8) can be adopted as practical drying laws for fixed beds of tree chips. The problem then is to predict one of the efficiencies, either η_t or η_p.

3.5 Estimation of drying efficiencies from empirical drying laws

From (3) and (4),

$$\frac{dW}{dt} = \frac{1}{(1 - w)^2}\frac{dw}{dt} = (1 + W)^2\frac{dw}{dt} \qquad (9)$$

The empirical drying law (5) gives

$$-\frac{dw}{dt} = bw_o, \qquad (10)$$

Then (7) yields

$$\eta_t = \frac{\Delta h_v m''_d w_o b}{G_1 c_{pa}(T_1 - T_a)(1 - w)^2} = \eta_{to}\left(\frac{1 - w_o}{1 - w}\right)^2 \qquad (11)$$

$$\eta_p = \frac{\Delta h_v m''_d w_o b}{G_1 c_{pa}(T_1 - T_s)(1 - w)^2} = \eta_{po}\left(\frac{1 - w_o}{1 - w}\right)^2 \qquad (12)$$

We have, using these equations, estimated η_{to} and η_{po} from the slopes b in Figs. 6--9. The physical and operating data required for the calculations are shown in Table 2. The bed loadings m''_d in the tests on spruce chips were 10--12 kg/m² and in those on maple chips, 16--17 kg/m². The enthalpy of vapourization Δh_v was evaluated at the inlet air saturation (wet-bulb) temperature T_s. The results are shown in Figs. 11 and 12.

The meaning of values of η_{po} greater than unity is considered in Sect. 4 Discussion. One obvious possible cause of such difficulty, though, is that the calculation basically requires an accurate estimate of dw/dt at $w \rightarrow w_o$, $t \rightarrow 0$. The empirical drying law (5) gives a good fit of w(t) at $w/w_o > 0.5$, but how well it describes dw/dt at small t is a different matter. Examination of integral or cumulative drying efficiencies in the following Section, 3.6, in fact indicates that the estimates of η_{to} and η_{po} from (5) for spruce are consistent but those for maple are too large.

Consistency for maple is, however, more nearly achieved by using a somewhat different drying law,

$$W/W_o = a - bt \quad . \tag{13}$$

This fits the data for maple well over a considerable range near t = 0, Figs. 13 and 14. With (13) as the drying law, (7) and (8) give

$$\eta_t = \frac{\Delta h_v m''_d W_o b}{G_1 c_{pa}(T_1 - T_a)} \tag{14}$$

$$\eta_p = \frac{\Delta h_v m''_d W_o b}{G_1 c_{pa}(T_1 - T_s)} \tag{15}$$

Values of η_t and η_p so estimated for maple are shown in Fig. 15. In drying with dry air, a = 1 and then $\eta_{to} = \eta_t$ and $\eta_{po} = \eta_p$. In drying with the humid air, however, a = 1.06. The values then calculated for η_t and η_p appear to be valid at W/W_o = 0.70--0.95, at least, but do not indicate the behaviour at $W/W_o > 0.95$.

3.6 Integral or cumulative drying efficiencies

Cumulative thermal and psychrometric drying efficiencies are defined by

$$m_d''(W_o - W)\Delta h_v = \bar{\eta}_t G_1 c_{pa}(T_1 - T_a)t \ , \tag{16}$$

$$m_d''(W_o - W)\Delta h_v = \bar{\eta}_p G_1 c_{pa}(T_1 - T_s)t \tag{17}$$

In words, the cumulative efficiency is the heat utilized to vapourize the moisture lost by the bed up to time t divided by the heat available for the process from the air supplied. Comparison with the differential forms (7) and (8) shows that

$$\bar{\eta}_t = \frac{1}{t}\int_o^t \eta_t dt = \frac{W_o - W}{-\int_{W_o}^{W} \frac{dW}{\eta_t}} \ . \tag{18}$$

$$\bar{\eta}_p = \frac{1}{t}\int_o^t \eta_p dt = \frac{W_o - W}{-\int_{W_o}^{W} \frac{dW}{\eta_p}} \tag{19}$$

These efficiencies are thus time-average or integral quantities. As shown by (16) and (17), they can be directly calculated from the experimental data whereas the determination of η_t and η_p involves differentiation to obtain dW/dt.

Our results are shown in Figs. 16--23 in graphs of $\bar{\eta}_t$ and $\bar{\eta}_p$ as functions of w/w_o. Figures 24 and 25 give cross-plots of $\bar{\eta}_t$ and $\bar{\eta}_p$ as functions of temperature at $w/w_o = 1/2$.

In the case of spruce being dried with dry air, there are sharp intercepts in Figs. 16 and 17 at $w = w_o$. These intercepts should coincide with η_{to} and η_{po} if (5) is an excellent representation of w(t) at $w \to w_o$. The agreement is indeed very close, Figs. 11 and 12.

3.7 Air temperature at bed exit

Figure 26 shows the exit air temperature T_2 for the runs on maple chips with dry air. These were unfortunately the only valid data obtained. A thermocouple insertion problem which was discovered too late spoiled the data for the other runs.

Figures 27 and 28 show the temperature ratios

$$\frac{T_1 - T_2}{T_1 - T_a} \, , \qquad \frac{T_1 - T_2}{T_1 - T_s}$$

as functions of w/w_o. These quantities are related to the instantaneous efficiencies η_t and η_p. The first closely approximates the fraction of the heat supplied in the drying air that is utilized for warming the bed and evaporating moisture. The second approximates the fraction of theoretically available heat in the air (that above the wet-bulb temperature) that is so utilized.

3.8 Drying curves for isolated chips in the sand bath

Single spruce chips were dried with dry air at the four temperature levels. The drying curves obtained for the eight chips used are shown in Fig. 29. The raw data are given in Appendix A. Equation 2 fits fairly well at w/w_o larger than 1/2. At 75, 90 and 100 °C, $a = 1.00$, but at 125 °C this coefficient is around 1.2. The slopes b, surprisingly, at 75, 90 and 100 °C are not significantly larger than in the fixed bed drying, Fig. 30. At 125 °C, a substantially larger value is however observed. It should be noted that these chips were of larger than average size (compare Tables 21 and 24 of Appendix A).

4. Discussion

4.1 Reliability of the results

The drying efficiencies for spruce, Figs. 16--19, look quite reasonable. There are a few data sets in Fig. 19 that show psychrometric efficiencies a little over unity, as high as 1.07. This could be accounted for by an overall error of no more than 5 % in the various experimental measurements (air flowrate, temperatures, wood moistures).

However, the drying efficiencies for the maple chips, Figs. 20--23, look high, and those in Fig. 23 for drying with humid air are very significantly too high, well beyond the bounds of expected experimental error. We have not yet discovered a reason for this excessive error and it appears that only a careful repetition of the work on maple would resolve the question. It should be noted that because of the short duration of the contracted work, an apparatus had to be assembled and results produced in a great hurry. There was no time for systematic check-out and some of the instrumentation, particularly that for flow measurement, was not of the best. It is clear that the determination of reliable values of the drying efficiencies requires very good measurements of all types.

A fairly good idea of what would be reasonable for maple is indicated by the air outlet temperatures, which were good, in the runs with dry air. We must expect that

$$\eta_t < \frac{T_1 - T_2}{T_1 - T_a} \quad , \quad \eta_p < \frac{T_1 - T_2}{T_1 - T_s}$$

Examination of the results on these temperature ratios, Figs. 27 and 28, then suggests that the maximum efficiencies in these runs must be such that $\eta_t < 0.73$ and $\eta_p < 0.85$.

To further explore this question, suppose that one kilogram in dry mass of maple chips at 20 °C with 65 % d.b. (39.4 % w.b.) initial moisture is to be dried to 33.3 % d.b. (25 % w.b.). It would appear from our results that the process is effectively roughly as follows:

[] heat the material from 20 °C to 50 °C. The heat capacity of the wood dry matter is about 1255 J/kg K while that of liquid water is 4180 J/kg K. The heat required is

$$[(0.65)(4180) + (1)(1255)][50 - 20] = 119200 \text{ J}$$

[] evaporate at 50 °C the moisture to be removed. The enthalpy of vapourization is 2370 kJ/kg. The heat required is thus

$$(0.65 - 0.333)(2370000) = 751300 \text{ J}$$

Thus 86.3 % of the total heat so required is utilized for evaporation. This indicates that, roughly, in our tests on maple chips,

$$\eta_t = 0.86 \frac{T_1 - T_2}{T_1 - T_a} ,$$

$$\eta_p = 0.86 \frac{T_1 - T_2}{T_1 - T_s} .$$

Then, from the conclusion of the preceding paragraph, $\eta_t < 0.63$ and $\eta_p < 0.73$.

A consistency test on the energy balance is possible which, however, fails to solve the mystery. Take, for example, the run on drying of maple chips with dry air supplied at 90 °C. At thirty minutes drying time, virtually all the moisture had been evaporated. From Fig. 26, we find that the time-average outlet air temperature T_2 over this period was 61.5 °C. At 30 minutes time the outlet air temperature was 80 °C and with the bed virtually dry and hottest on the inlet side, we may assume that the bed was at about 80 °C average temperature. The relevant operating data and physical properties are:

$m''_d = 16.2$ kg/m²

$W_o = 0.621$

$G_1 = 0.495$ kg/m²s

$T_o = 20$ °C

$c_{pa} = 1010$ J/kg K

$c_{pv} = 2010$ J/kg K (heat capacity of water vapour)

$c_{pd} = 1255$ J/kg K (heat capacity of wood dry matter)

$\Delta h_v = 2460$ kJ/kg at 20 °C

The process can now be treated as follows. The heat given up by the air in 30 minutes is

$$G_1 c_{pa}(T_1 - T_2)t = (0.495)(1010)(90 - 61.5)(30)(60)$$

$$= 2.56 \times 10^7 \text{ J}$$

The energy taken by the water evaporated and the wood dry matter is estimated by the following operations:

[] evaporate the moisture at 20 °C. The heat requirement is

$$m_d'' W_o \Delta h_v = (16.2)(0.621)(2460000) = 2.47 \times 10^7 \text{ J}$$

[] from Fig. 27 we deduce that a typical outlet temperature T_2 for the leaving water vapour was 58 °C. The heat requirement to warm the vapour to this level is

$$m_d'' W_o c_{pv}(T_2 - T_o) = (16.2)(0.621)(2010)(58 - 20)$$

$$= 0.077 \times 10^7 \text{ J}$$

[] finally, at 30 minutes time the bed consists of wood dry matter at about 80 °C. The heat required to so warm the dry matter is

$$m_d'' c_{pd}(T_2 - T_o) = (16.2)(1255)(80 - 20) = 0.122 \times 10^7 \text{ J}$$

The total energy consumed by the process is thus

$$(2.47 + 0.0077 + 0.122)(10^7) = 2.67 \times 10^7 \text{ J},$$

compared to 2.56×10^7 J supplied by the air. This is as close a check as we could wish for. It does not, therefore, shed any light on the problem of the evidently too-high thermal efficiencies occurring at times in the subject run.

4.2 Application of the results

The graphs of mean drying efficiency vs. reduced moisture content, Figs. 16--23, afford an easy and very meaningful way of predicting dryer performance. For a given relative moisture loss w/w_o is fixed. The graphs then give η_t or η_p. When these are known, the drying time can be calculated from (16) and (17). The effect of air-inlet temperature is obtained by interpolation, possibly using cross-plots like Figs. 24 and 25.

It should be noted that the effect of bed thickness is expressed through the bed loading m''_d. Although the effects of variations in bed loading m''_d, mass air velocity G_1 and initial moisture content w_o were not investigated here, we are confident that the correlations based on the drying efficiency concept express the primary effects of these variables. Examination of the mechanisms involved suggests that the secondary effects--those that cause redistribution in the energy budget--are relatively weak and become substantial only under large variation of m''_d, G_1 and w_o. Thus application of our correlations to different values of these quantities from those employed here should be practically valid provided that the changes are not excessive. In our judgement, reasonably good results can be expected for m''_d and G_1 from 1/2 to 2 times the present values, and for initial moisture contents of 35--55 % w.b.

The dominant fact of the drying of tree chips, provided that sufficiently deep beds are employed, is simply that over the practically interesting range of moisture contents most of the sensible enthalpy of the drying air above the wet-bulb temperature goes to evaporate moisture. Variation of m''_d, G_1 and w_o, unless carried to extremes, can only produce rather modest changes in this balance.

4.3 Comparisons with the literature

A literature review was not one of the tasks set in the subject contract. However, we have become aware of two activities in Canada. Dr. Marc Schneider, Professor of Wood Science and Technology at the University of New Brunswick, is studying forced-air drying of tree chips using unheated ambient air [1]. Dr. Paul Watkinson of the Department of Chemical Engineering, University of British Columbia, is studying drying of hog fuel for PAPRICAN (the Pulp and Paper Research Institute of Canada), but we have not seen his results.

Two other studies have come to our attention. Riley and Drechsel [2] investigated a number of approaches to tree chip drying, using ambient air, solar-heated air, and diluted combustion gases. Dynamic Systems Inc. [3] examined the application of geothermal energy.

The conclusions of the three published studies cited above agree in broad outline with the present findings. It would be useful if they provided some quantification of the secondary effects in hot-air drying alluded to in the preceding section but they do not.

Table 1. Operating conditions of the fixed-bed drying experiments

Tree chips:	softwood (spruce), hardwood (maple)
Bed thickness:	76 mm (3 in.)
Bed inlet air velocity based on empty column:	0.50 m/s (110 fpm)
Bed inlet air temperature:	75, 90, 100, 125 °C
Bed inlet air humidity:	virtually zero or air saturated at 50 °C
Moisture content of chips:	aimed for 50% w.b., in fact around 35--50 % for spruce chips and 35--38 % for maple chips

Table 2. Data for calculation of drying efficiencies

c_{pa} = 1010 J/kg °C, T_a = 20 °C

$G_1 = \rho_1 U_1$, U_1 = 0.51 m/s

T_1, °C	H_1^a	ρ_1, kg/m^3	G_1, kg/m^{2}s	T_s^b, °C	Δh_{vs}, kJ/kg
75	0	1.016	0.516	25	2442
	0.086	1.016	0.516	52	2378
90	0	0.974	0.495	29	2433
	0.086	0.974	0.495	53	2375
100	0	0.948	0.482	31	2428
	0.086	0.948	0.482	54	2373
125	0	0.888	0.451	35	2419
	0.086	0.888	0.451	55	2370

[a] Ambient air was taken at the controlled room temperature of T_a = 20 °C and is assumed to have been dry. Humidified air was obtained by sparging through water at 50 °C and is assumed to have been saturated at 50 °C, giving an absolute humidity of H_1 = 0.086 kg/kg

[b] For dry air, T_s is the wet-bulb temperature corresponding to the dry-bulb temperature T_1. For the humidified air, T_s is the wet-bulb temperature of air with an absolute humidity of 0.086 kg/kg and temperature T_1.

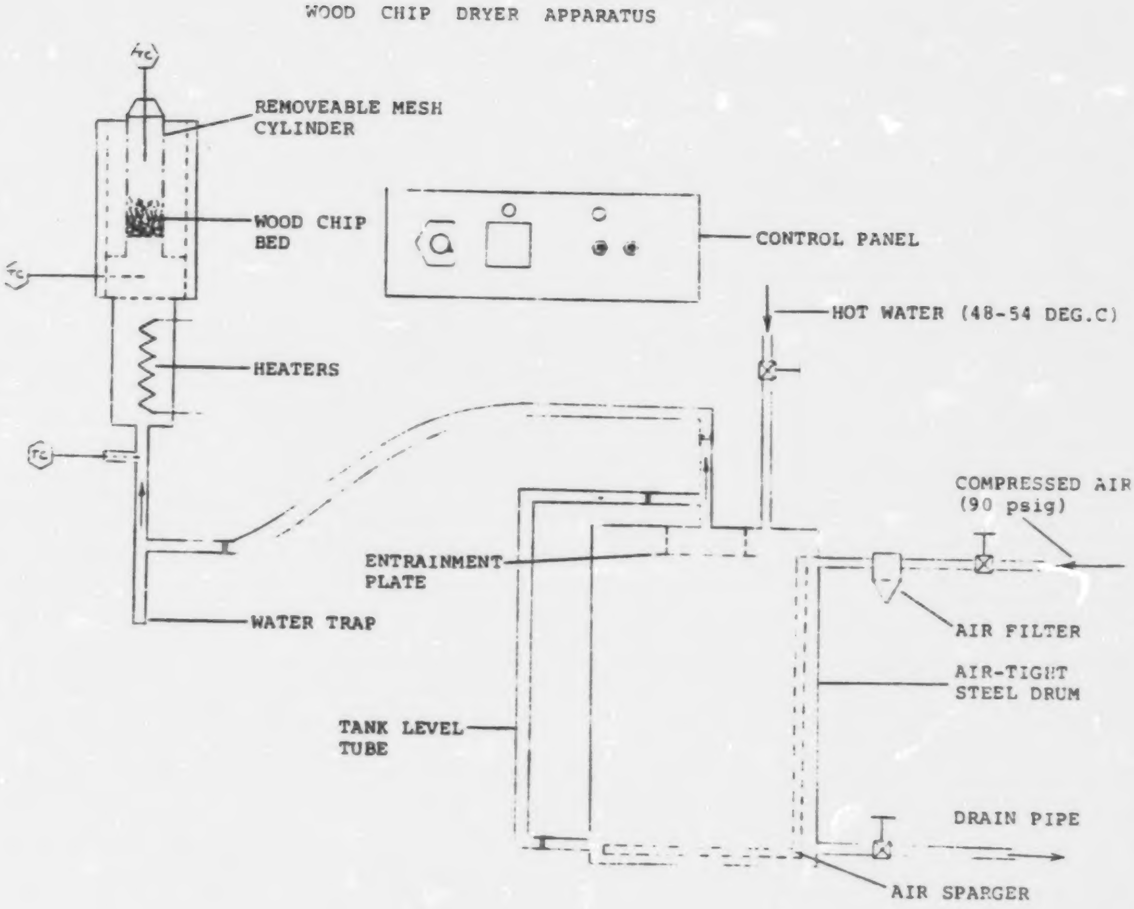

WOOD CHIP DRYER APPARATUS
TC
REMOVEABLE MESH CYLINDER
WOOD CHIP BED
TC
CONTROL PANEL
HOT WATER (48-54 DEG.C)
HEATERS
TC
COMPRESSED AIR (90 psig)
ENTRAINMENT PLATE
WATER TRAP
AIR FILTER
AIR-TIGHT STEEL DRUM
TANK LEVEL TUBE
DRAIN PIPE
AIR SPARGER

Fig. 1. Apparatus: humidifier drum, heater and fixed-bed dryer

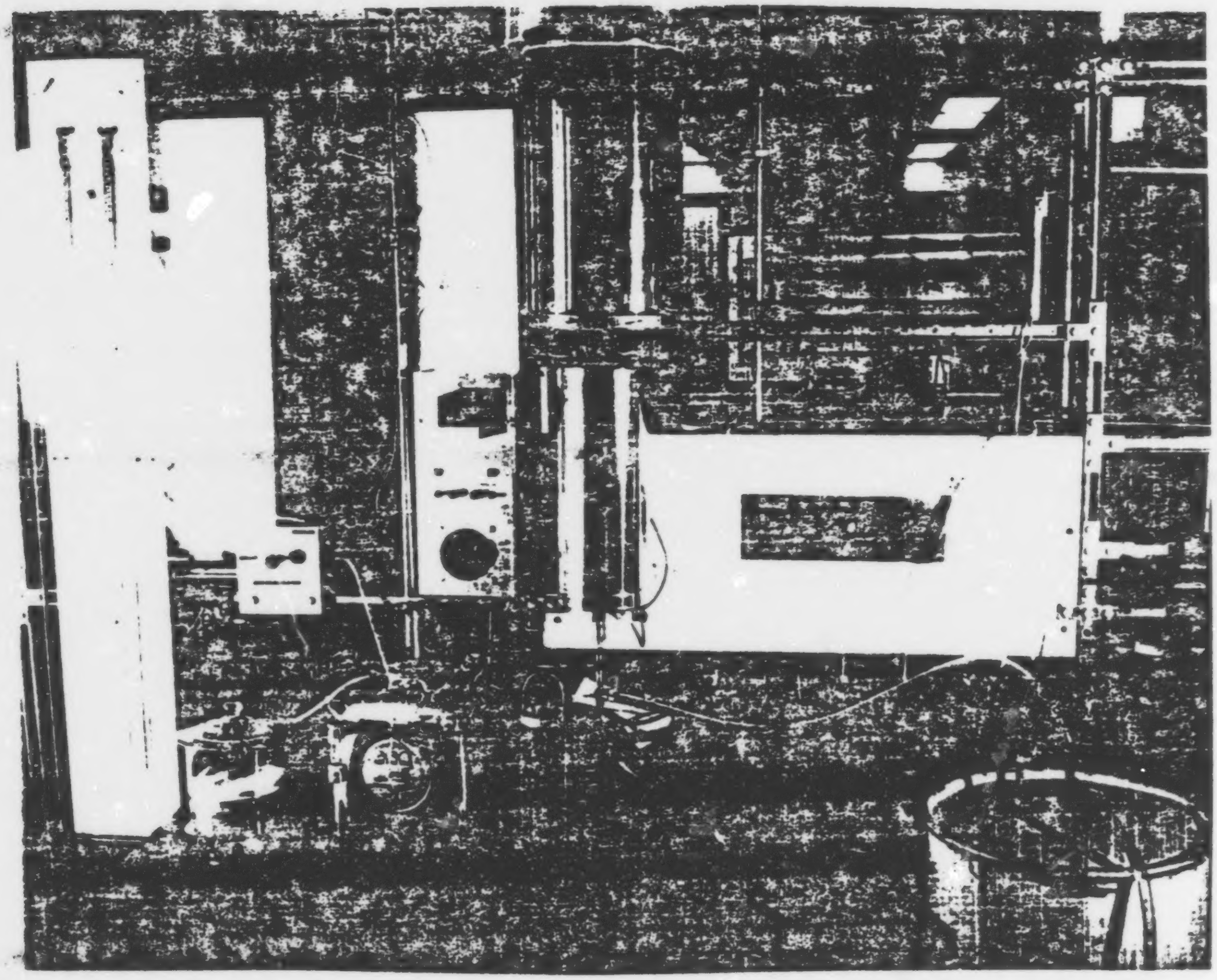


Fig. 2. View of dryer, top of humidifier drum, and instruments

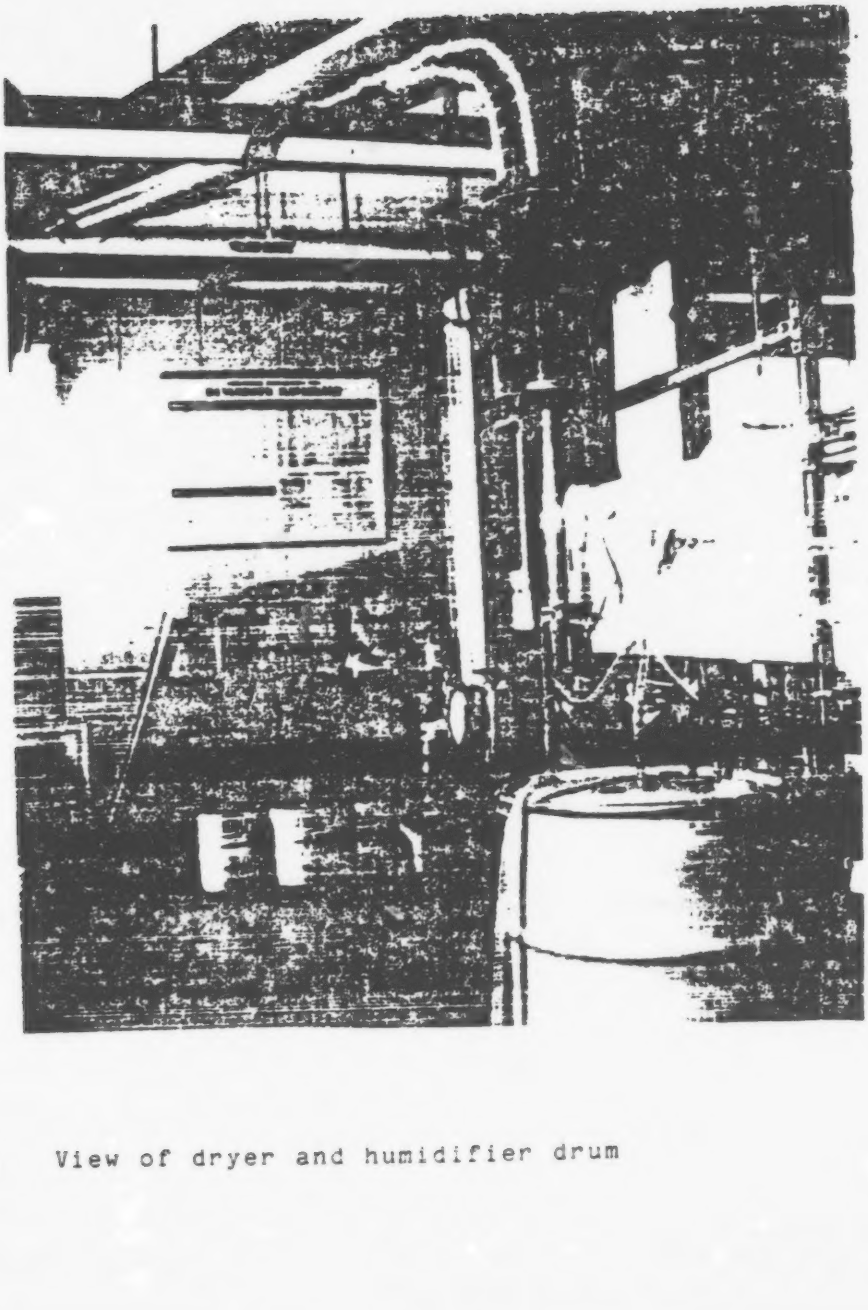


Fig. 3. View of dryer and humidifier drum

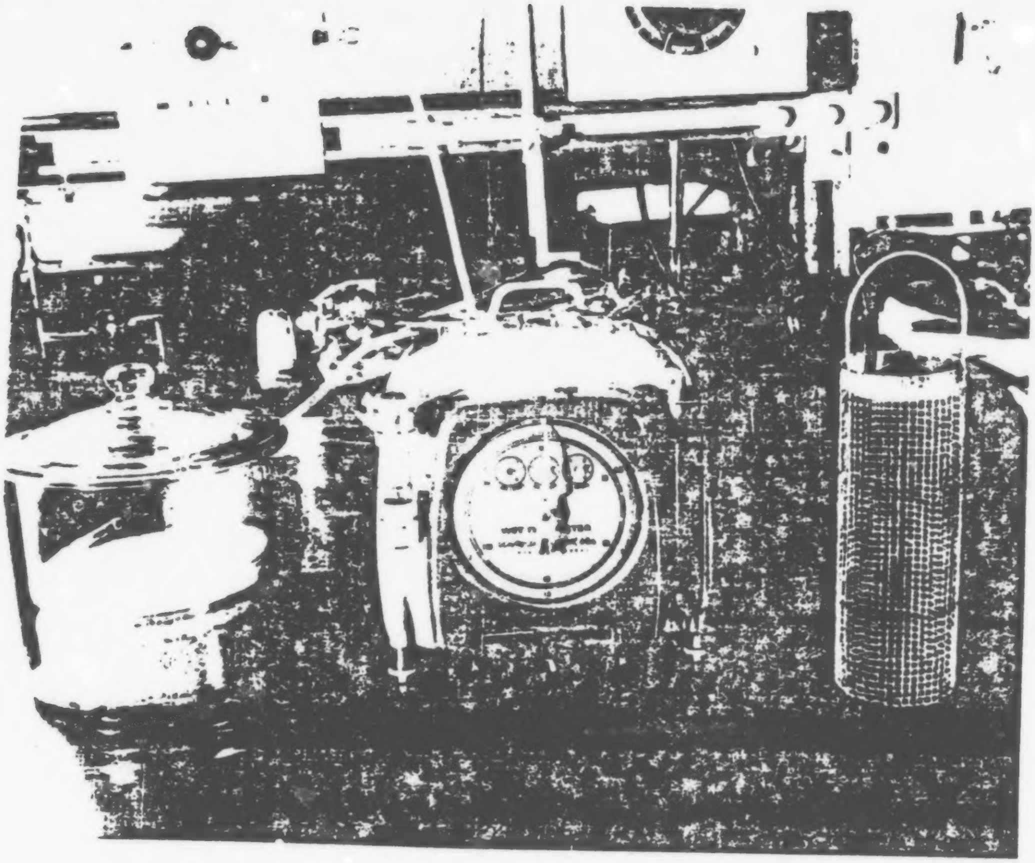


Fig. 4. Wire mesh cylinder for holding the bed

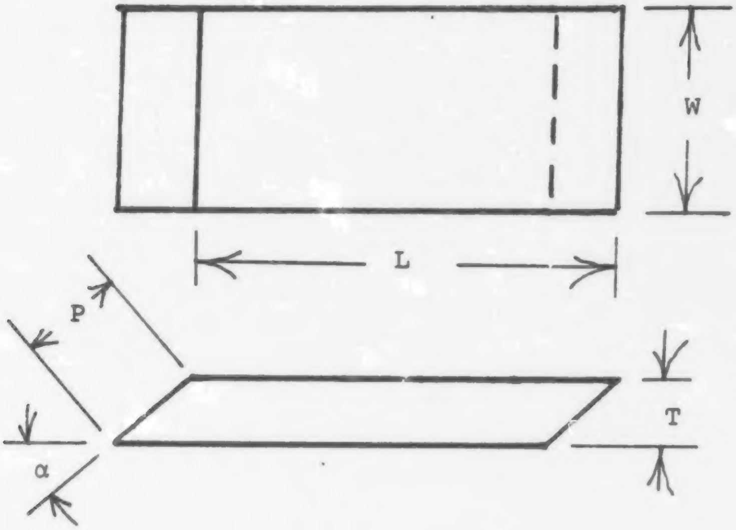


Fig. 5. Geometry of a tree chip

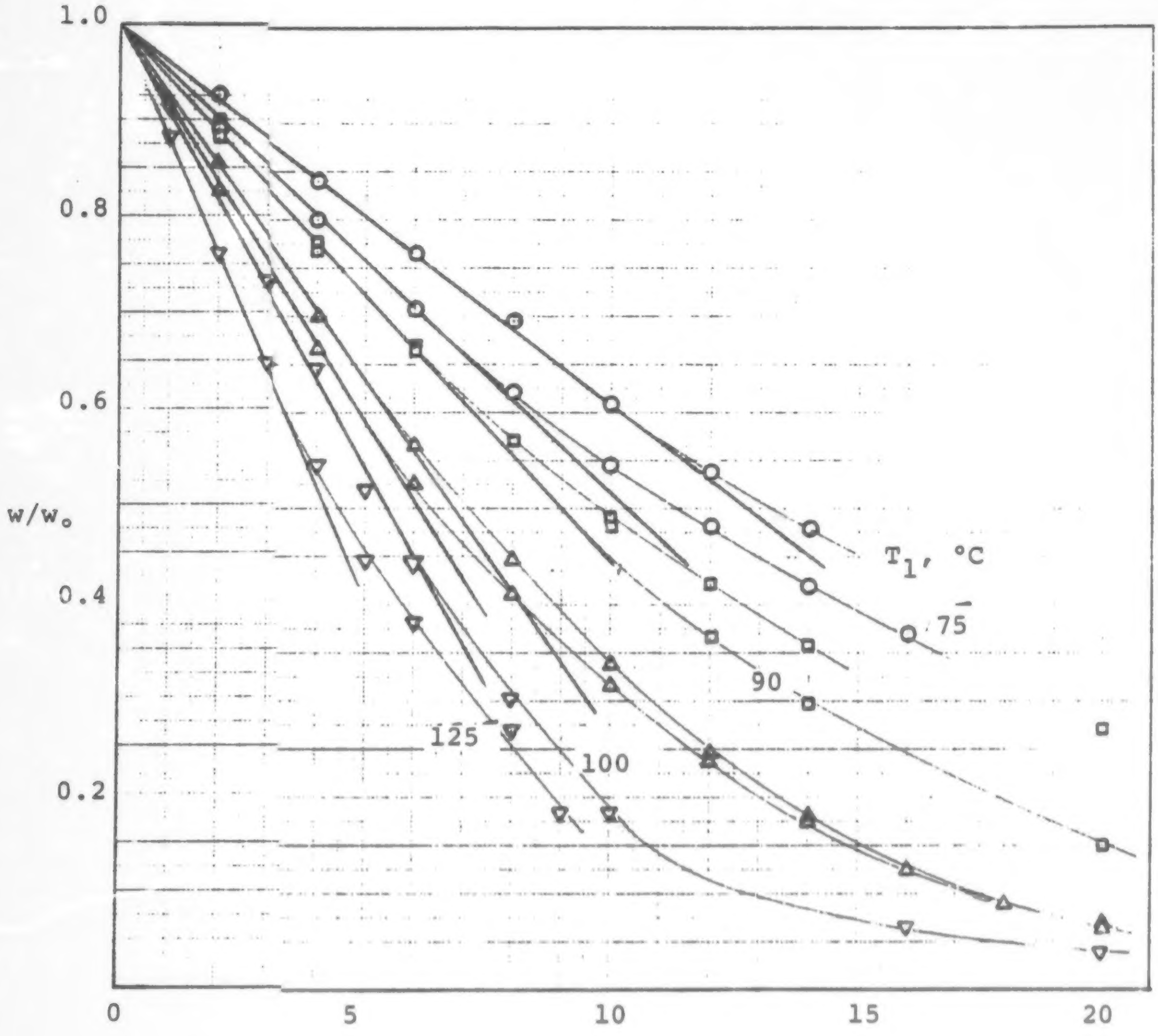


Fig. 6. Drying of spruce chips with dry air: reduced moisture content w.b. vs. time with inlet air temperature as parameter, initial moisture content w_o = 0.32--0.39. All runs were carried out in duplicate.

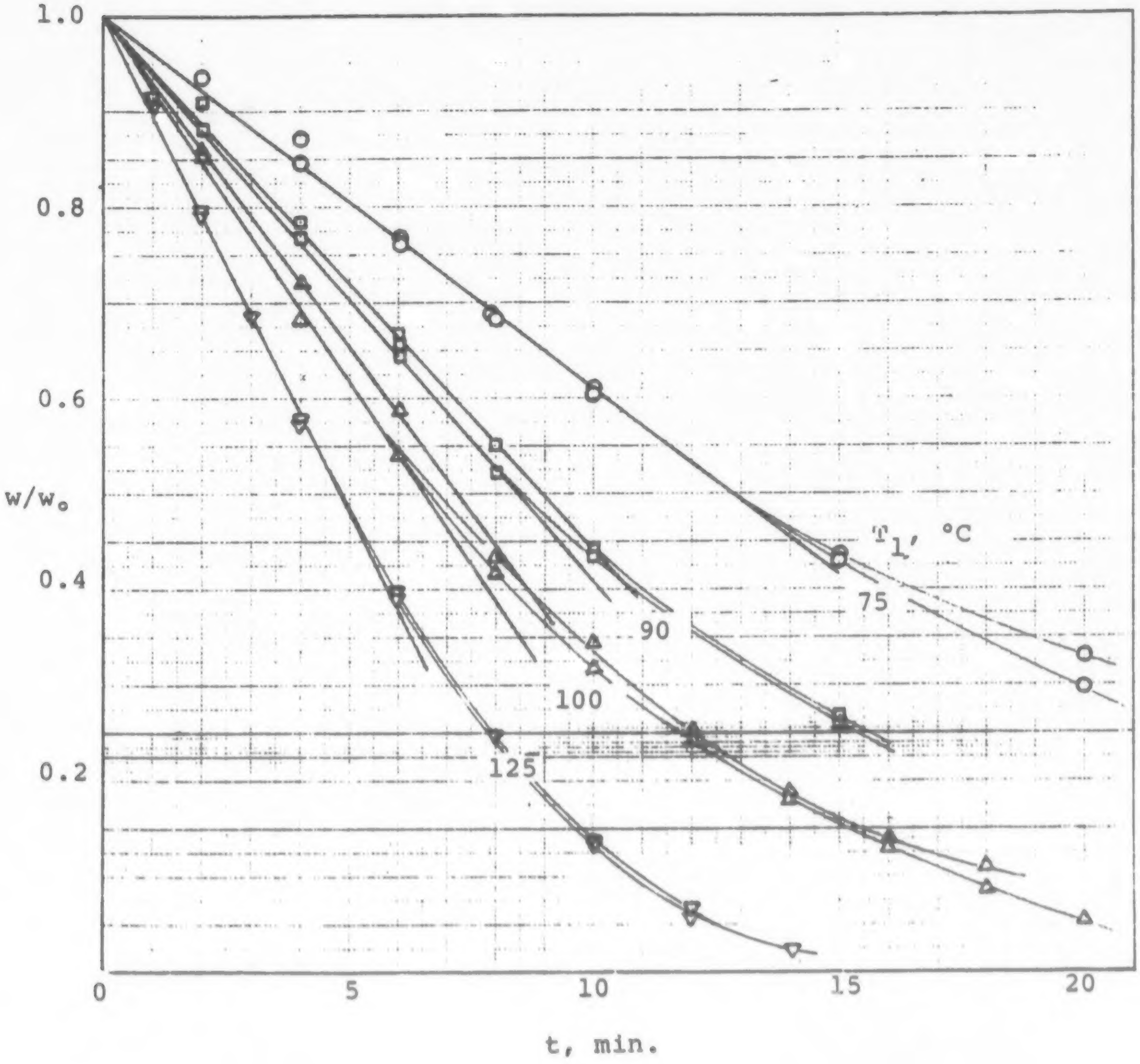


Fig. 7. Drying of spruce chips with humid air: reduced moisture content w.b. vs. time with inlet air temperature as parameter, initial moisture content w_o = 0.32--0.39

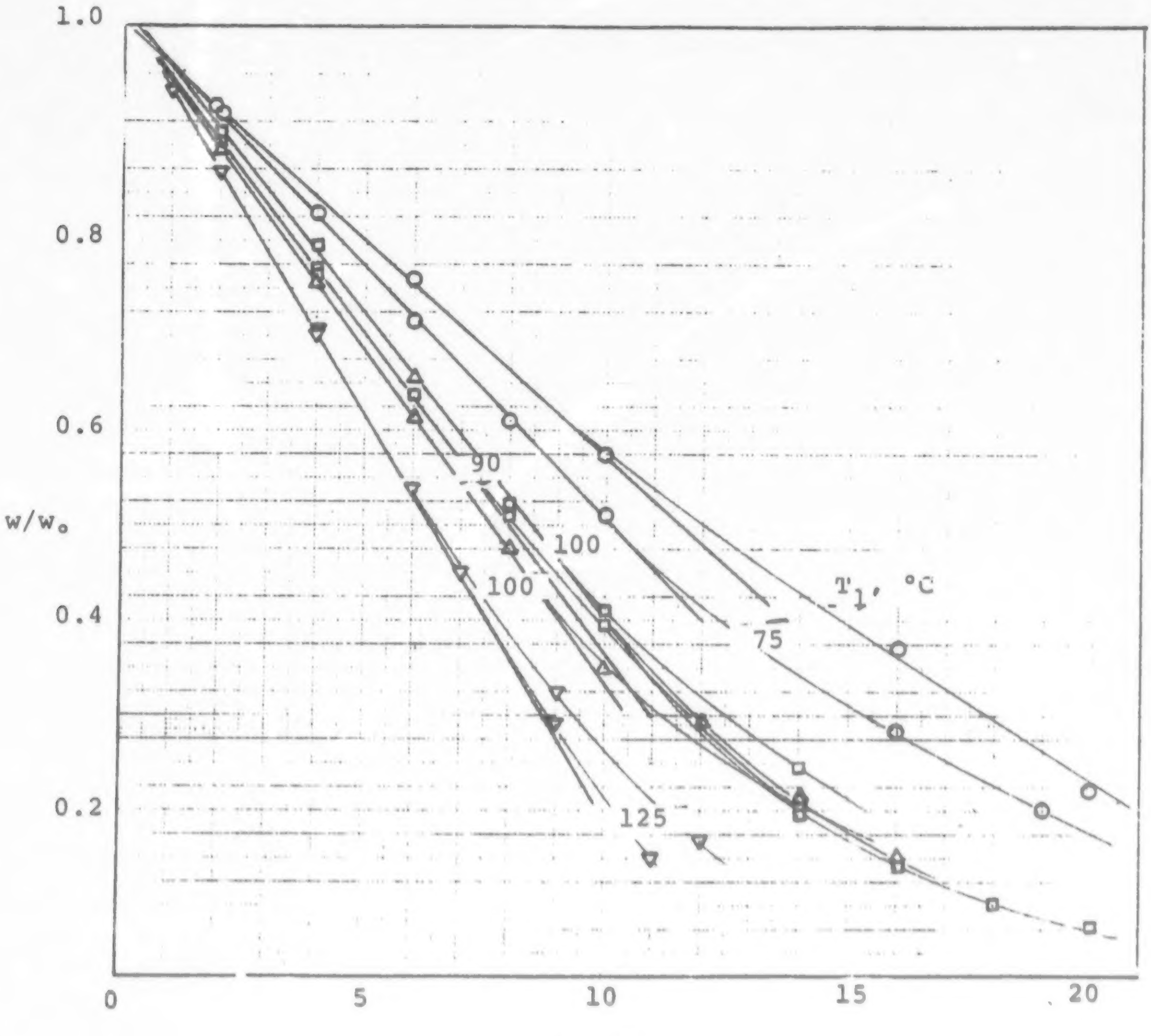


Fig. 8. Drying of maple chips with dry air: reduced moisture content w.b. vs. time with inlet air temperature as parameter, initial moisture w_o = 0.35--0.38

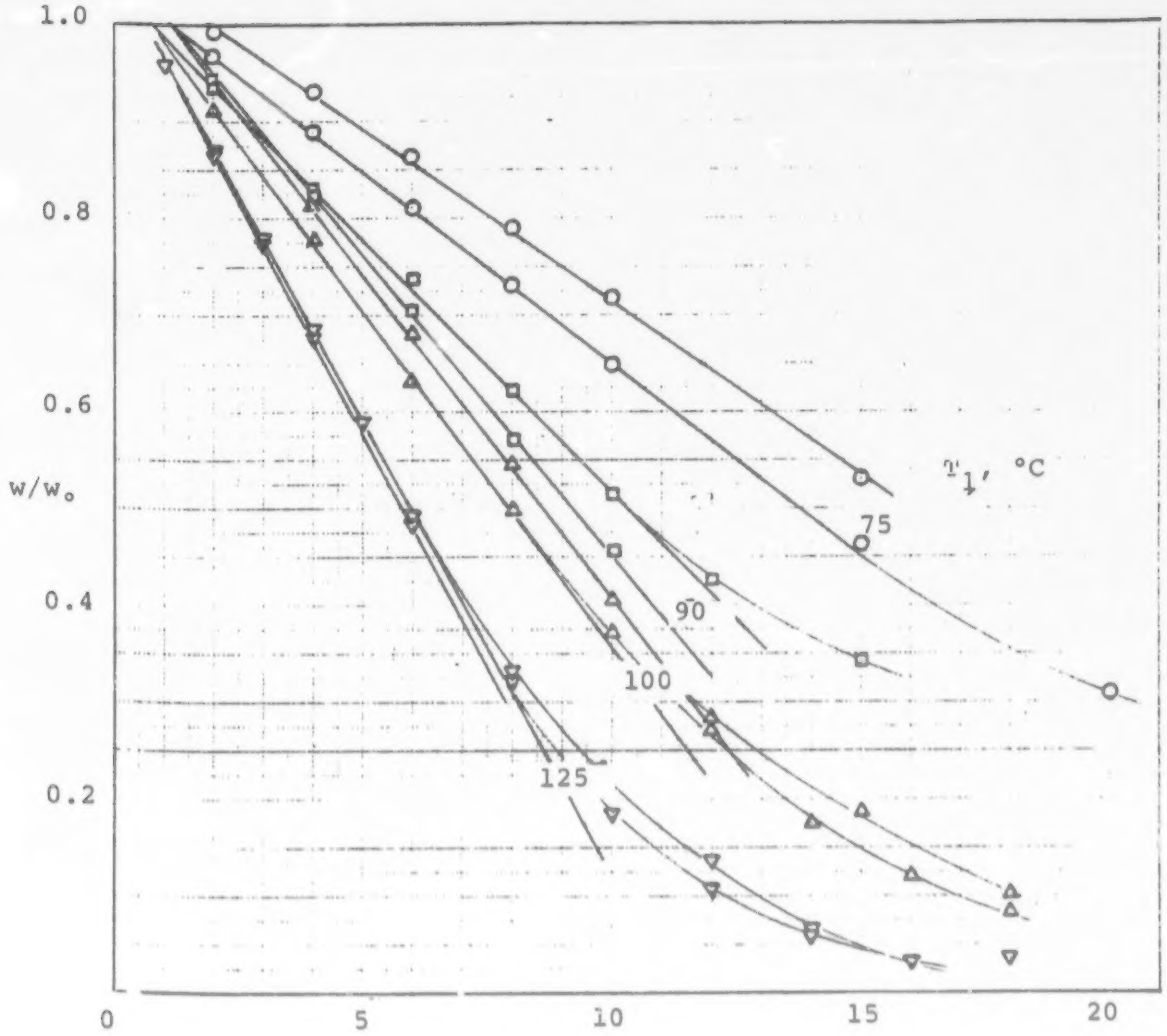
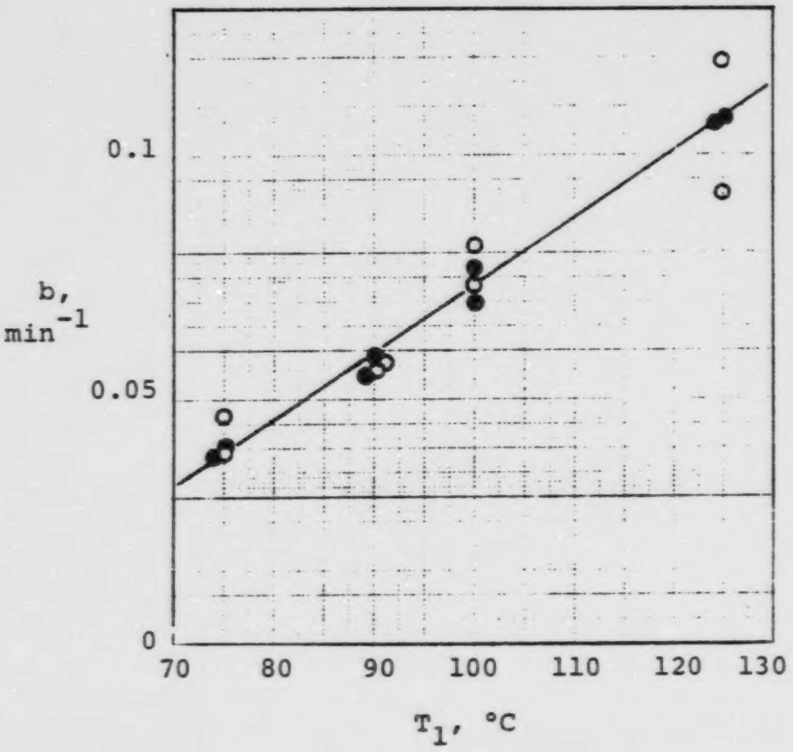


Fig. 9. Drying of maple chips with humid air: reduced moisture content w.b. vs. time with inlet air temperature as parameter, initial moisture w_o = 0.35--0.38



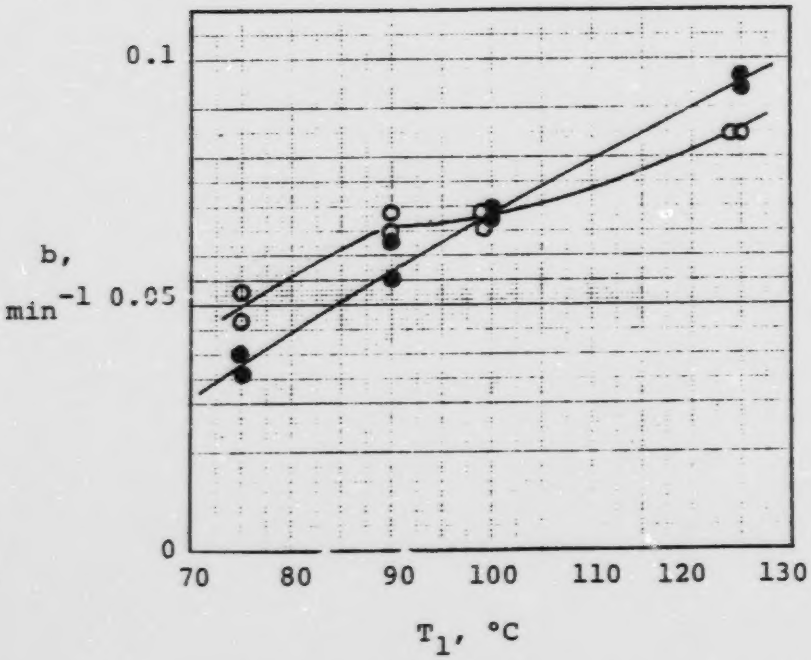


Fig. 10. The coefficient b in the initial linear drying law $w/w_o = a - bt$ as a function of inlet air temperature for top, (a), drying of spruce and bottom, (b), drying of maple. Open circles denote drying with dry air, shaded circles drying with humid air.

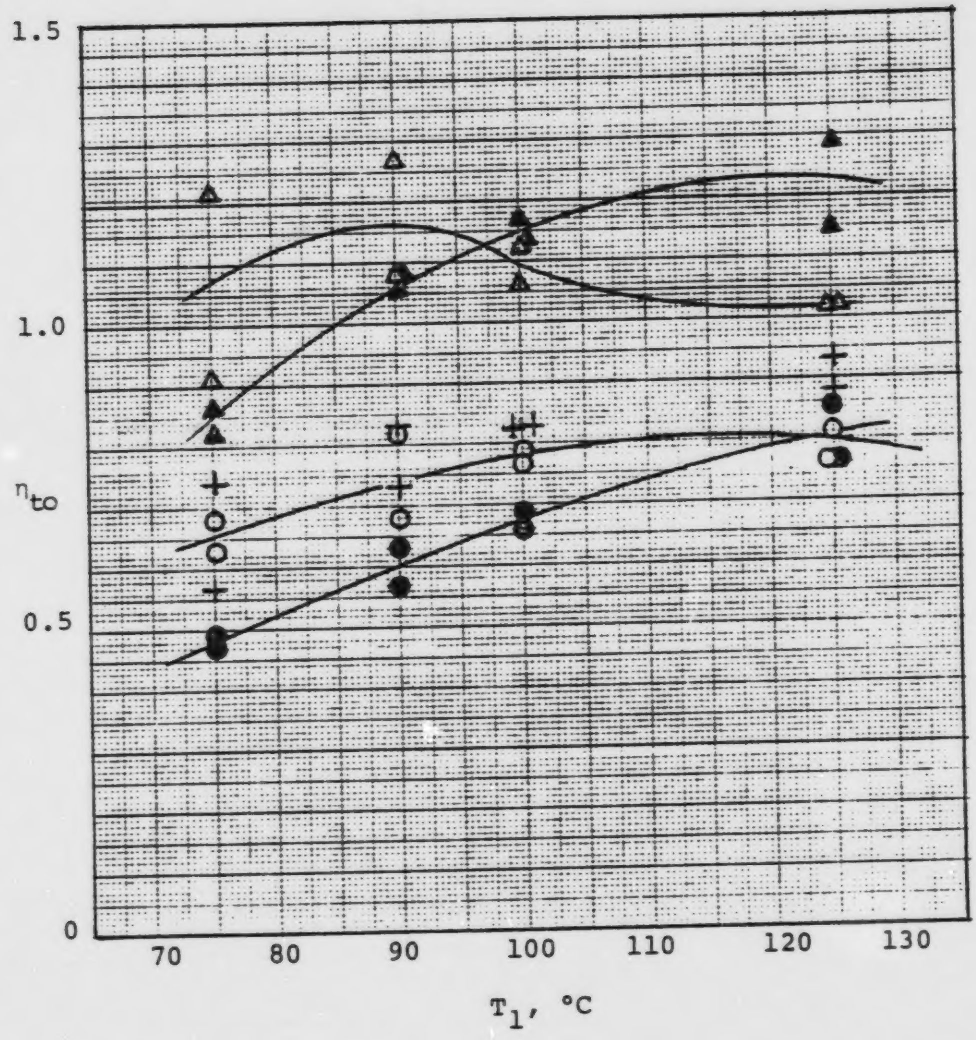


Fig. 11. Initial thermal drying efficiency deduced from the initial drying law $w/w_o = a - bt$ as a function of inlet air temperature. Circles denote spruce, triangles maple, open symbols drying with dry air, shaded symbols drying with humid air. Crosses represent initial values of the integral drying efficiency for drying spruce with dry air.

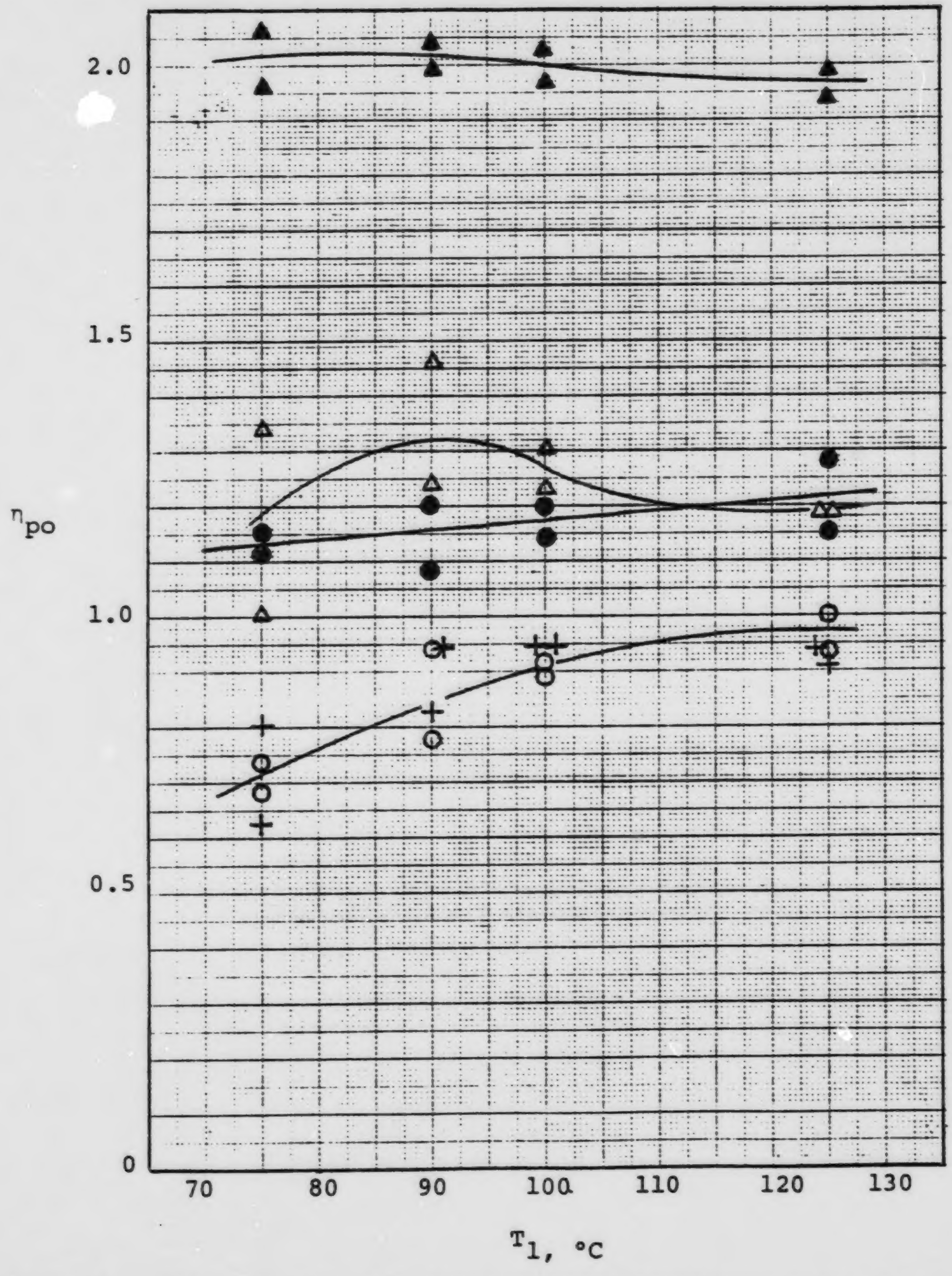


Fig. 12. Initial psychrometric drying efficiency deduced from the initial drying law $w/w_o = a - bt$ as a function of inlet air temperature. Explanation of symbols: see Fig. 11.

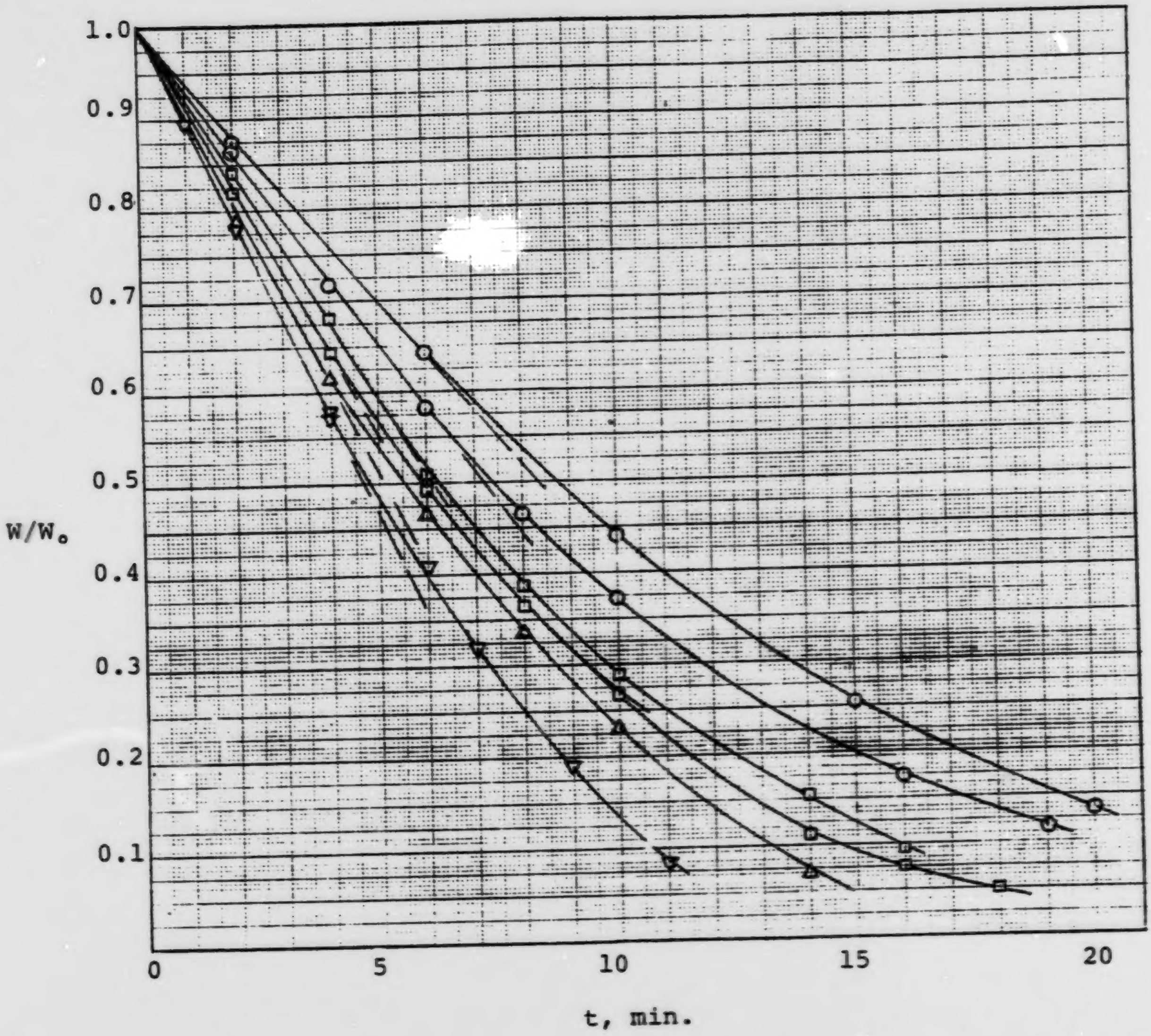


Fig. 13. Drying of maple chips with dry air: reduced moisture content d.b. vs. time with inlet air temperature as parameter, initial moisture W_o = 0.54--0.62

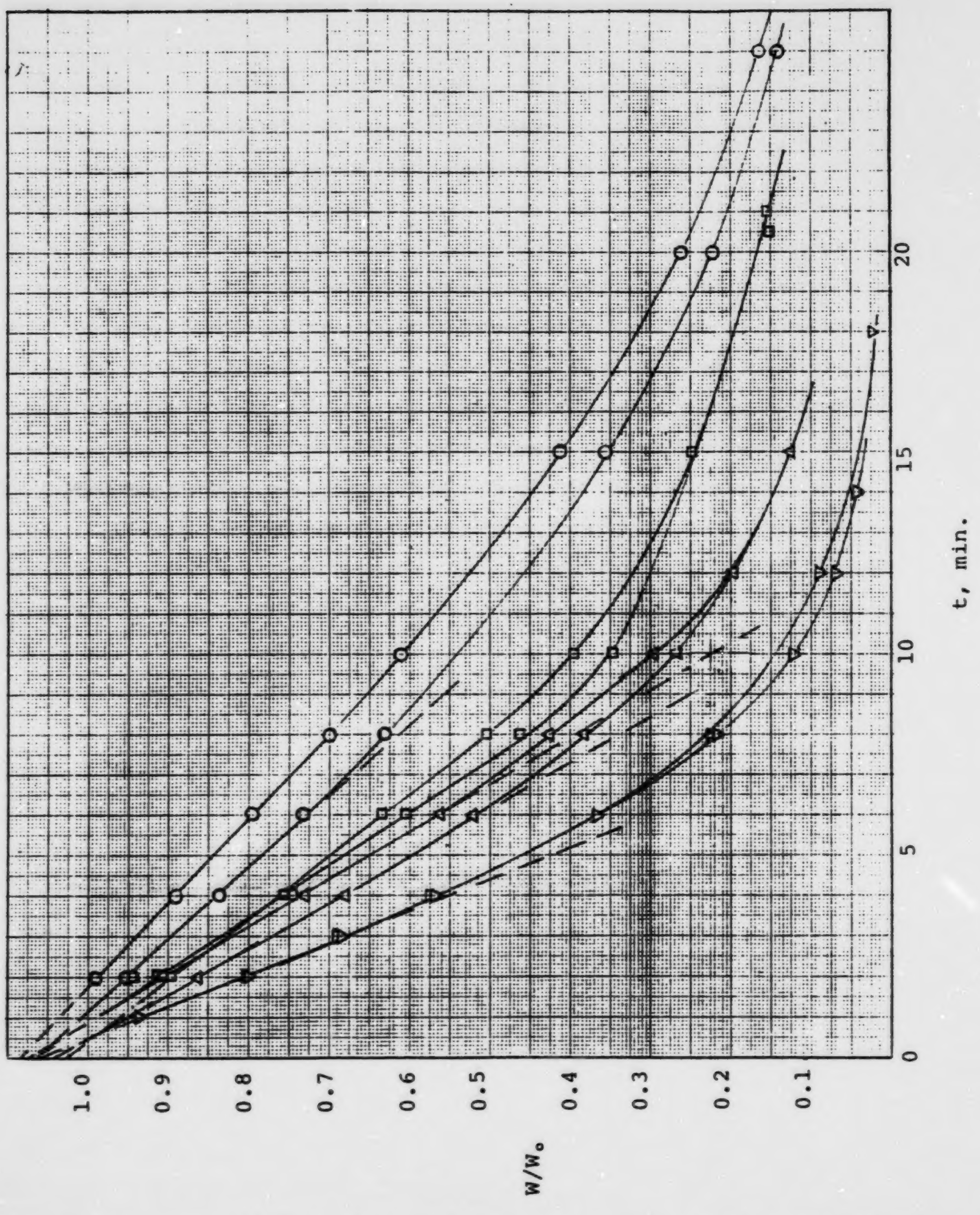


Fig. 14. Drying of maple chips with humid air: reduced moisture content d.b. vs. time with inlet air temperature as parameter, initial moisture W_o = 0.54--0.62

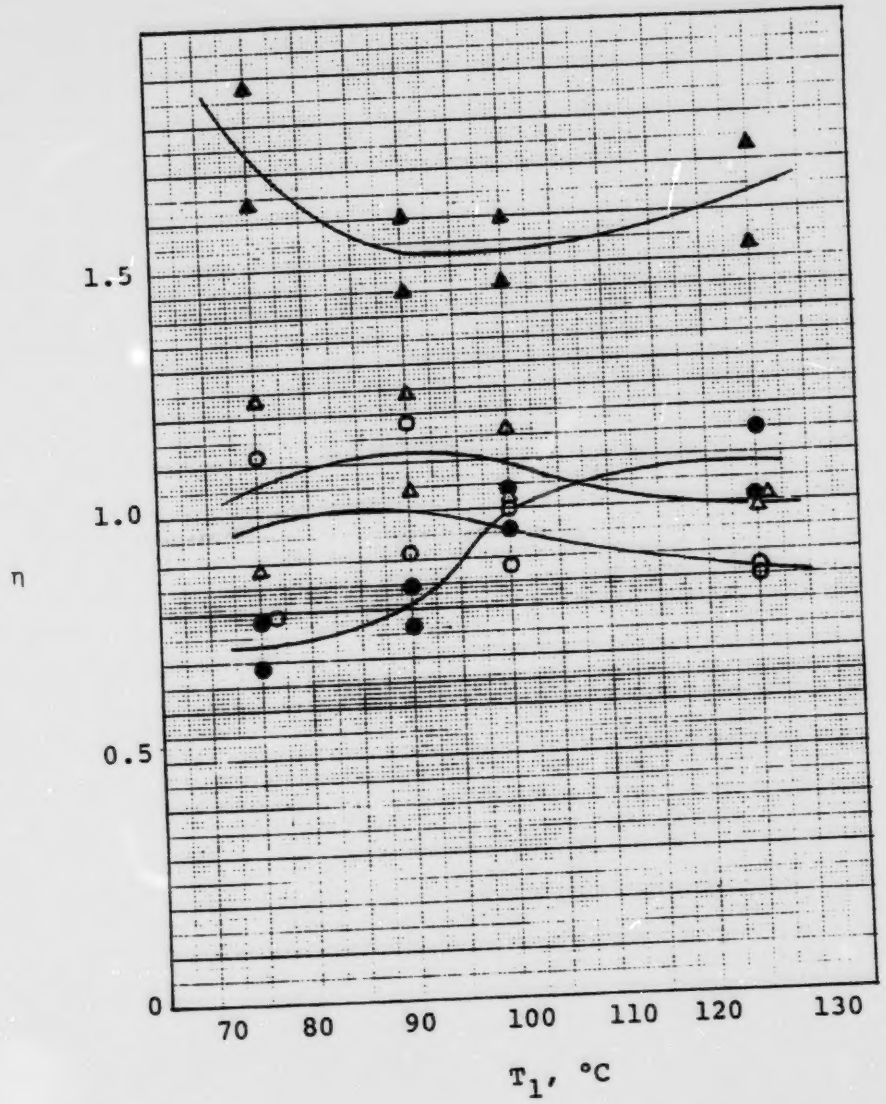


Fig. 15. Initial drying efficiency deduced from the initial drying law $W/W_o = a - bt$ for maple chips. Circles denote the thermal efficiency η_{to}, triangles the psychrometric efficiency η_{po}, open symbols drying with dry air, and closed symbols drying with humid air.

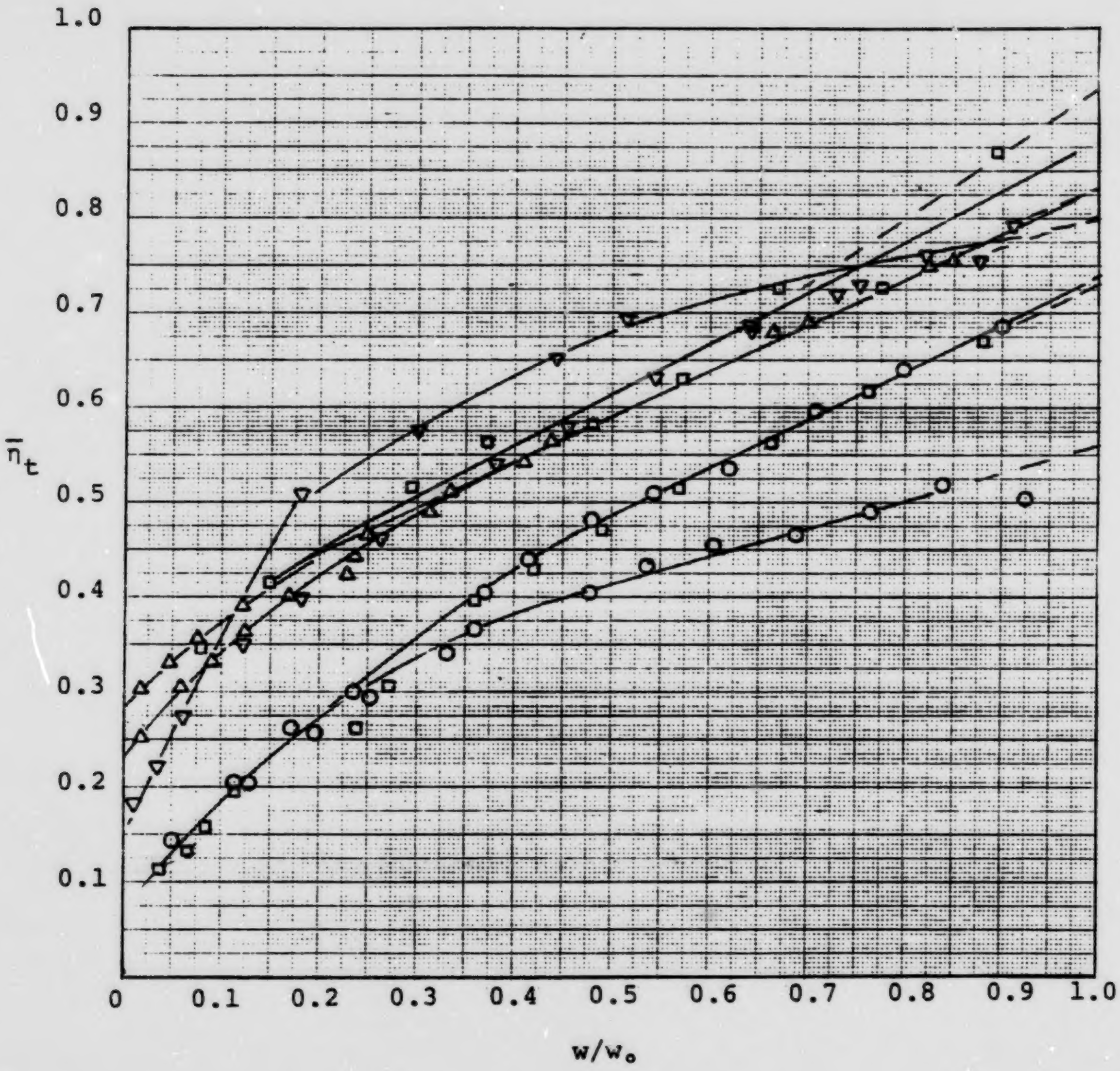


Fig. 16. Integral thermal efficiency as a function of reduced moisture content w.b. for drying spruce chips with dry air. Key to symbols:

Inlet air temperature, °C:	75	90	100	125
Symbol:	○	□	△	▽

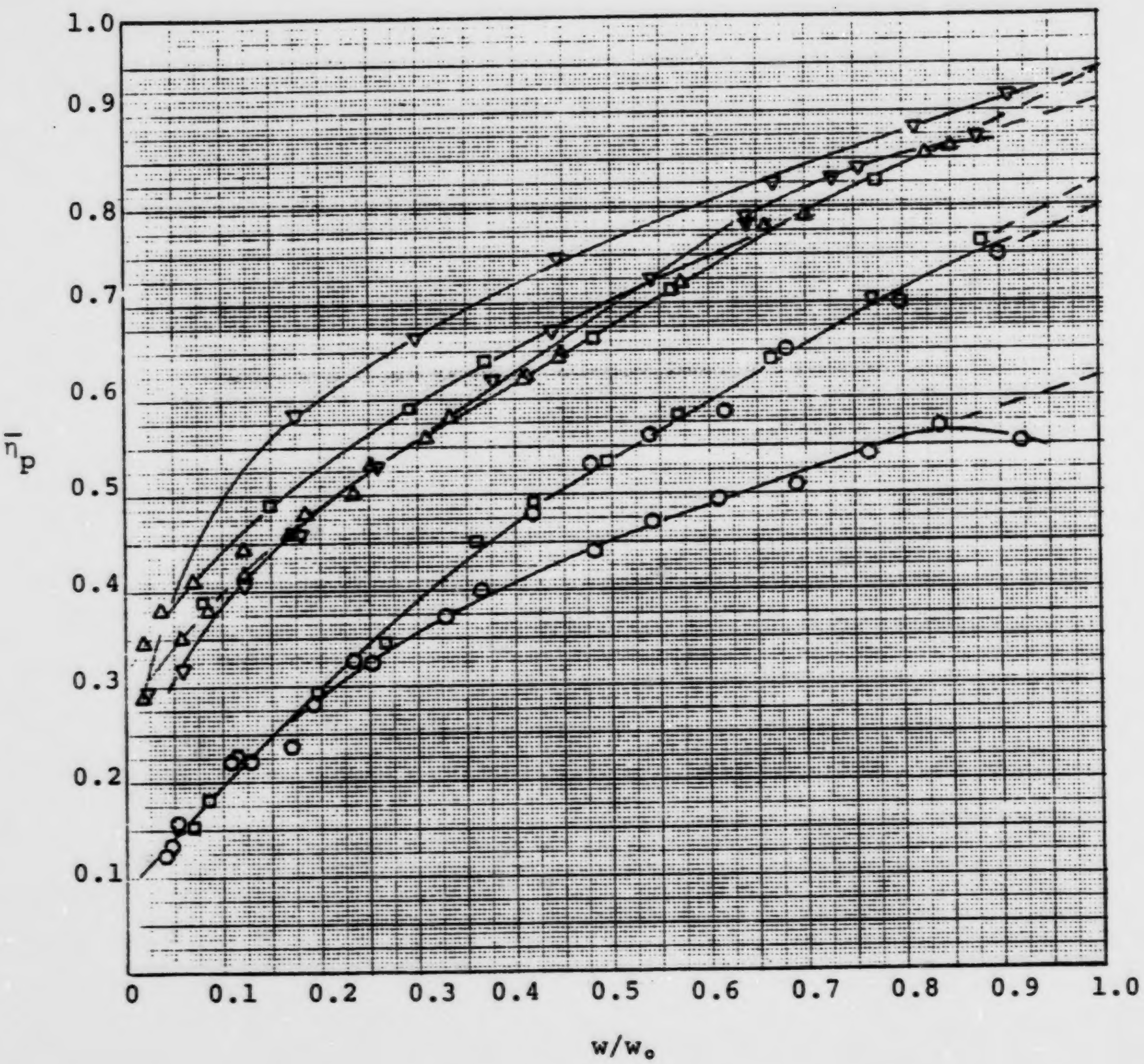


Fig. 17. Integral psychrometric efficiency as a function of reduced moisture content w.b. for drying spruce chips with dry air. Key to symbols:

Inlet air temperature T_1, °C:	75	90	100	125
Symbol:	○	□	Δ	∇

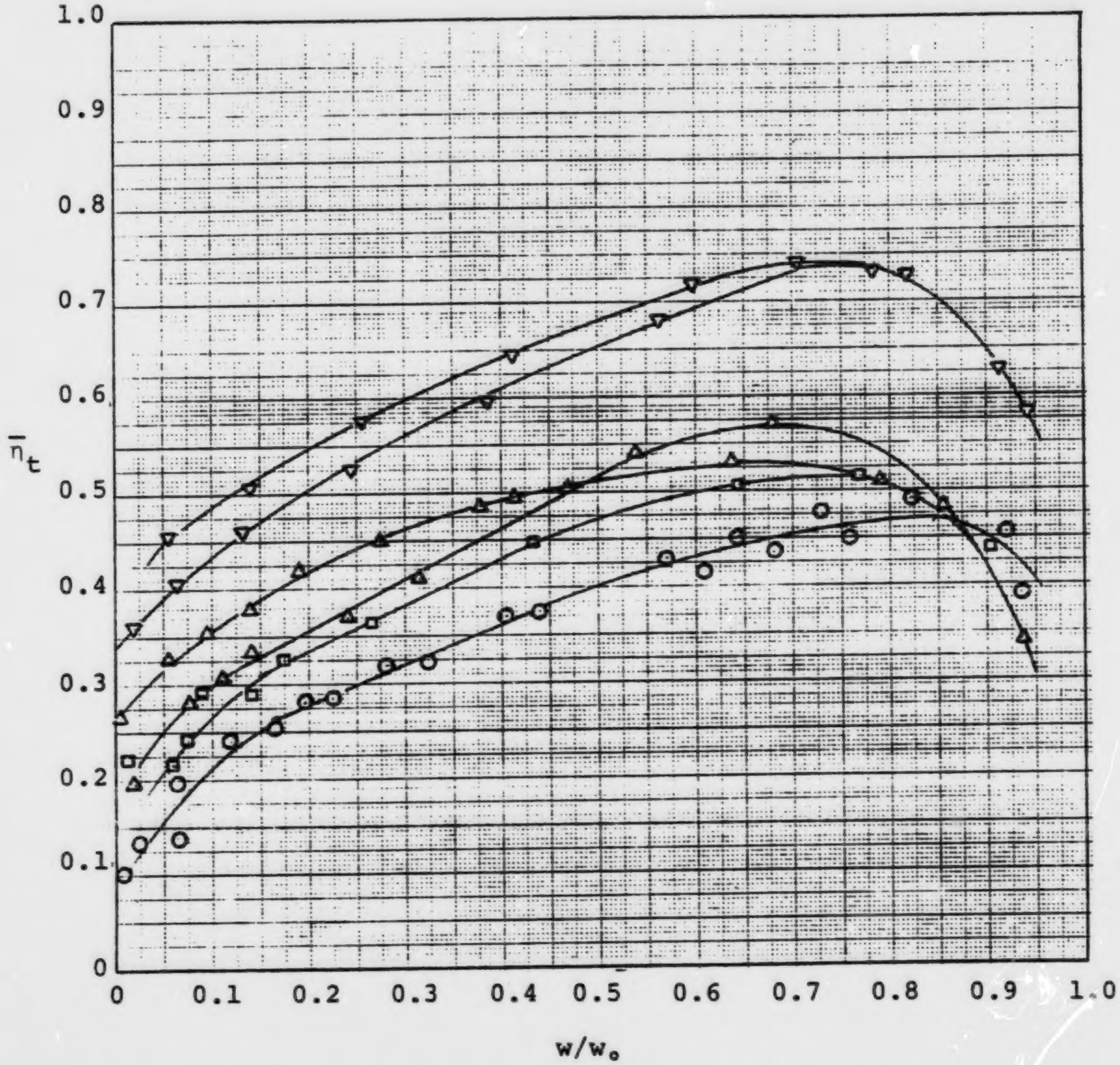


Fig. 18. Integral thermal efficiency as a function of reduced moisture content w.b. for drying spruce chips with humid air. Key to symbols:

Inlet air temperature, T_1, °C:	75	90	100	125
Symbol:	○	□	△	▽

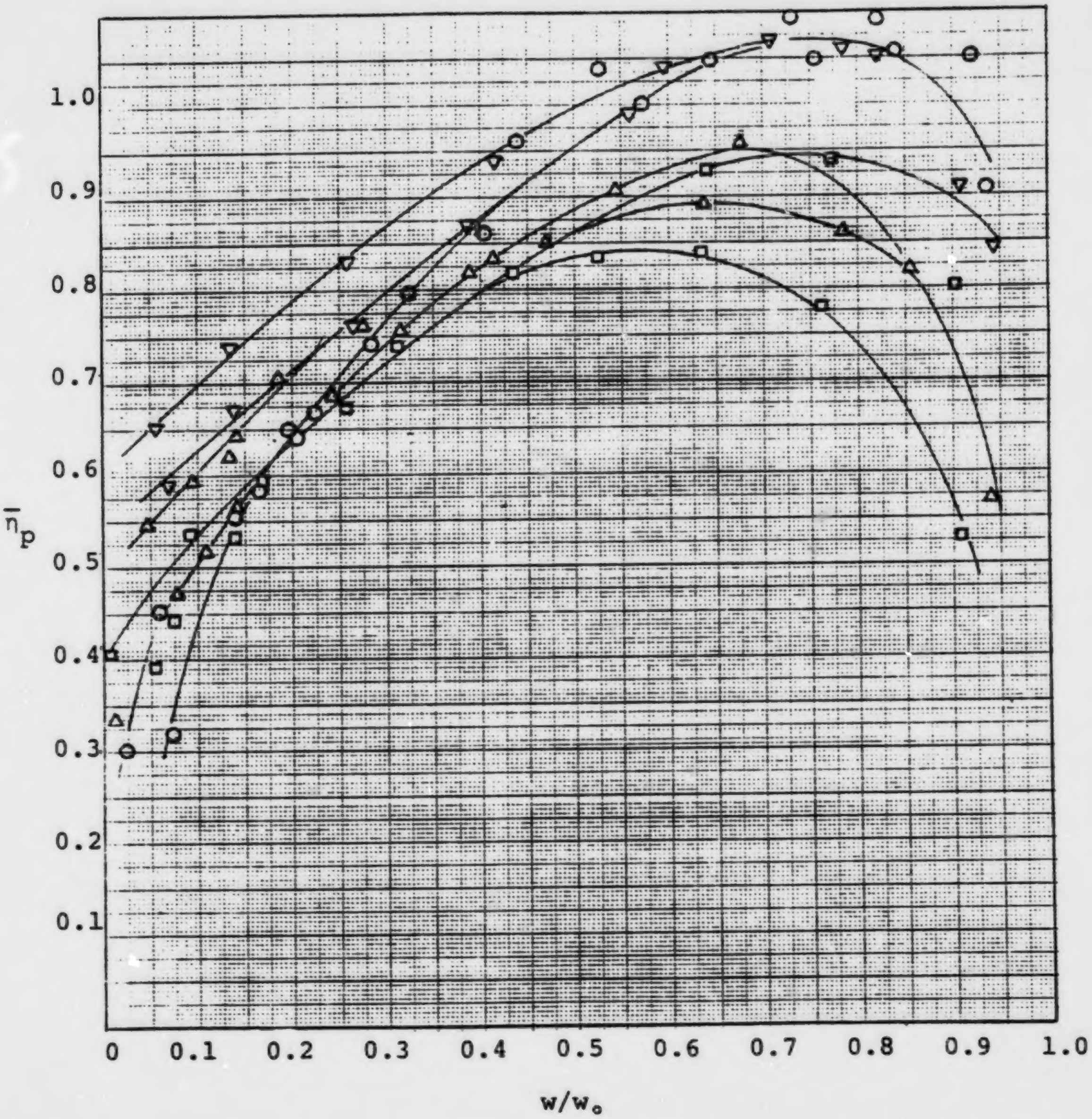


Fig. 19. Integral psychrometric efficiency as a function of reduced moisture content w.b. for drying spruce chips with humid air. Key to symbols:

Inlet air temperature T_1, °C:	75	90	100	125
Symbol:	○	□	△	▽

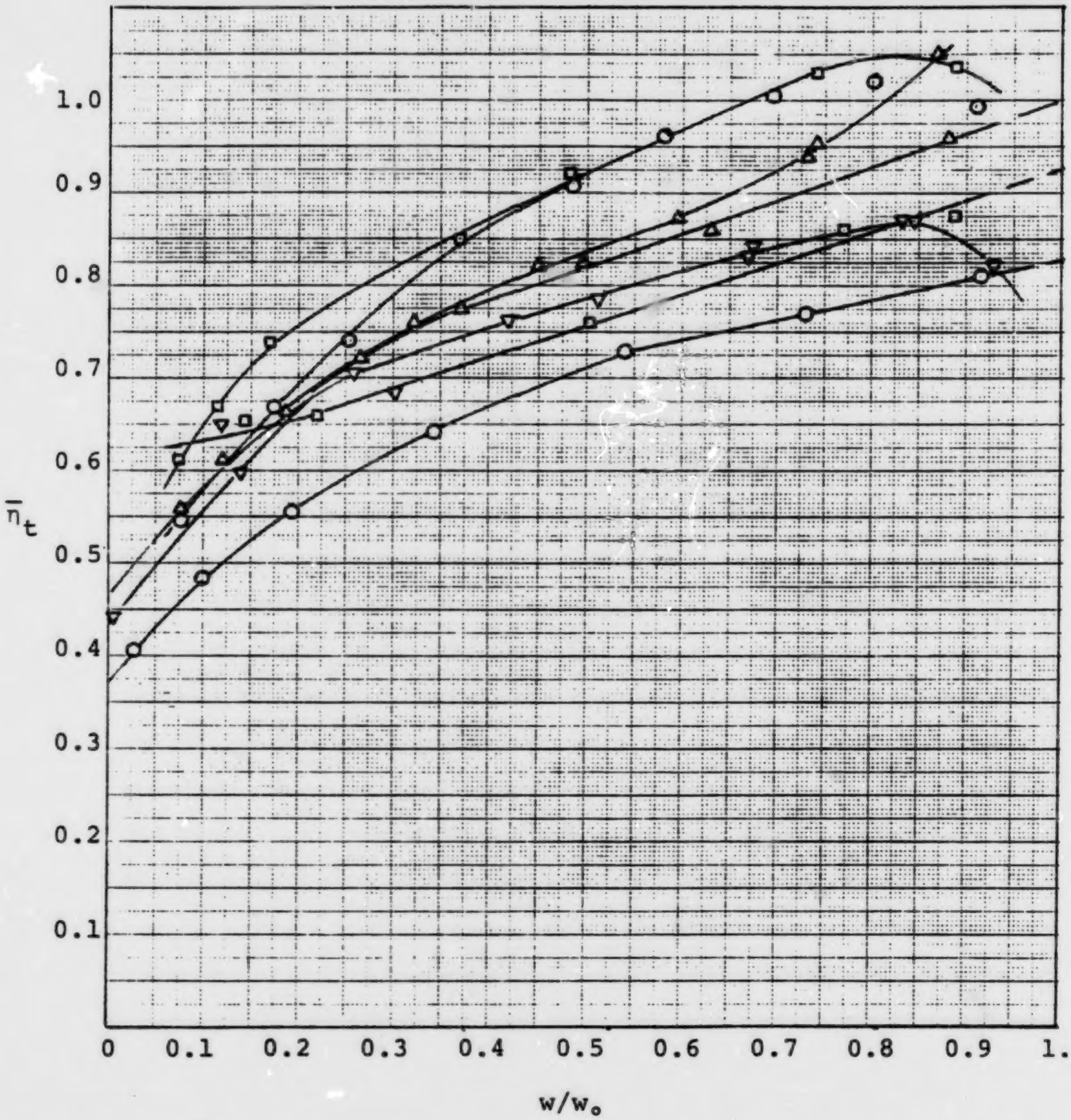


Fig. 20. Integral thermal drying efficiency as a function of reduced moisture content w.b. for drying maple chips with dry air. Key to symbols:

Inlet air temperature T_1, °C:	75	90	100	125
Symbol:	○	□	△	▽

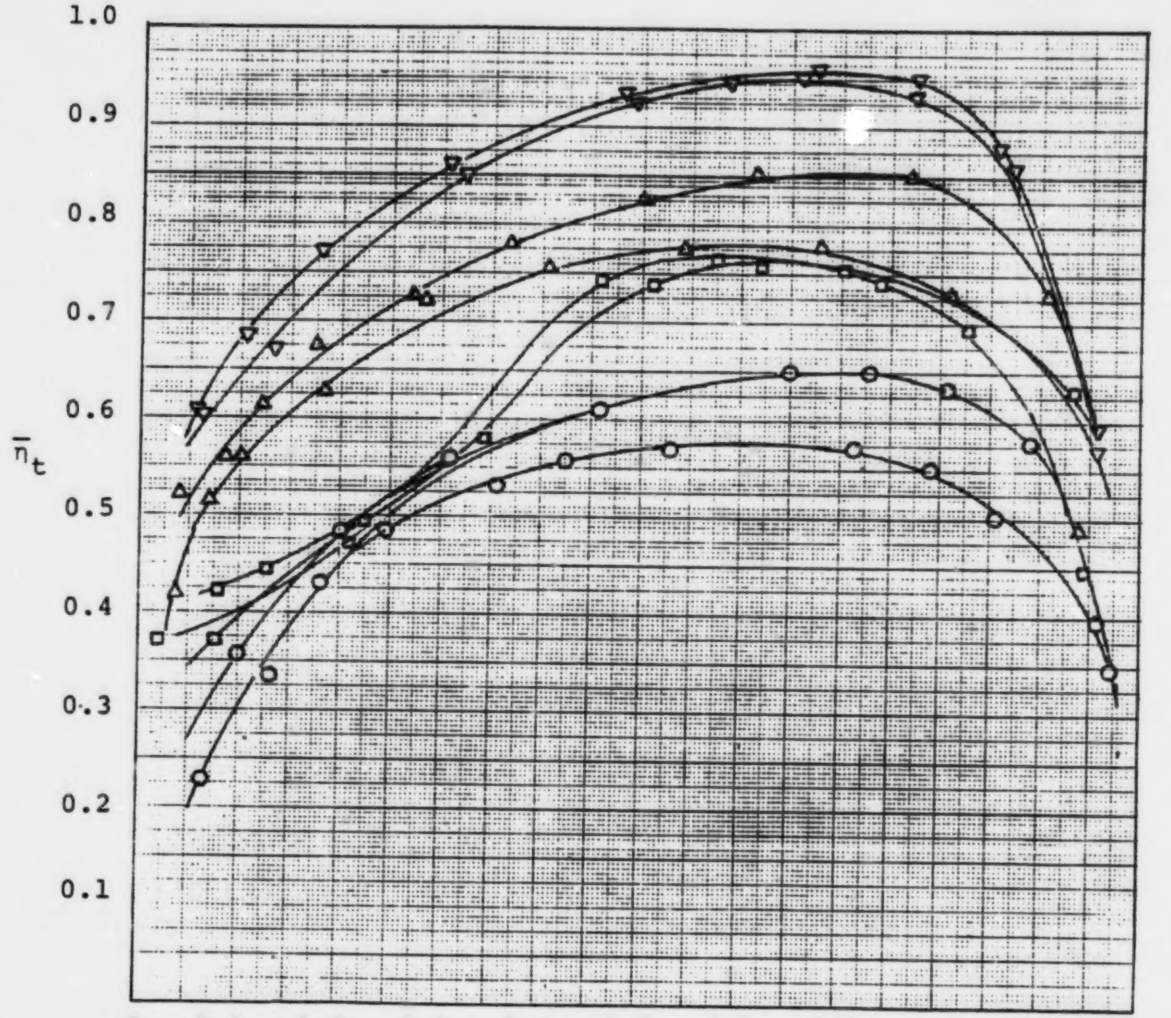


Fig. 21. Integral thermal drying efficiency as a function of reduced moisture content w.b. for drying maple chips with humid air. Key to symbols:

Inlet air temperature T_1, °C:	75	90	100	125
Symbol:	○	□	△	▽

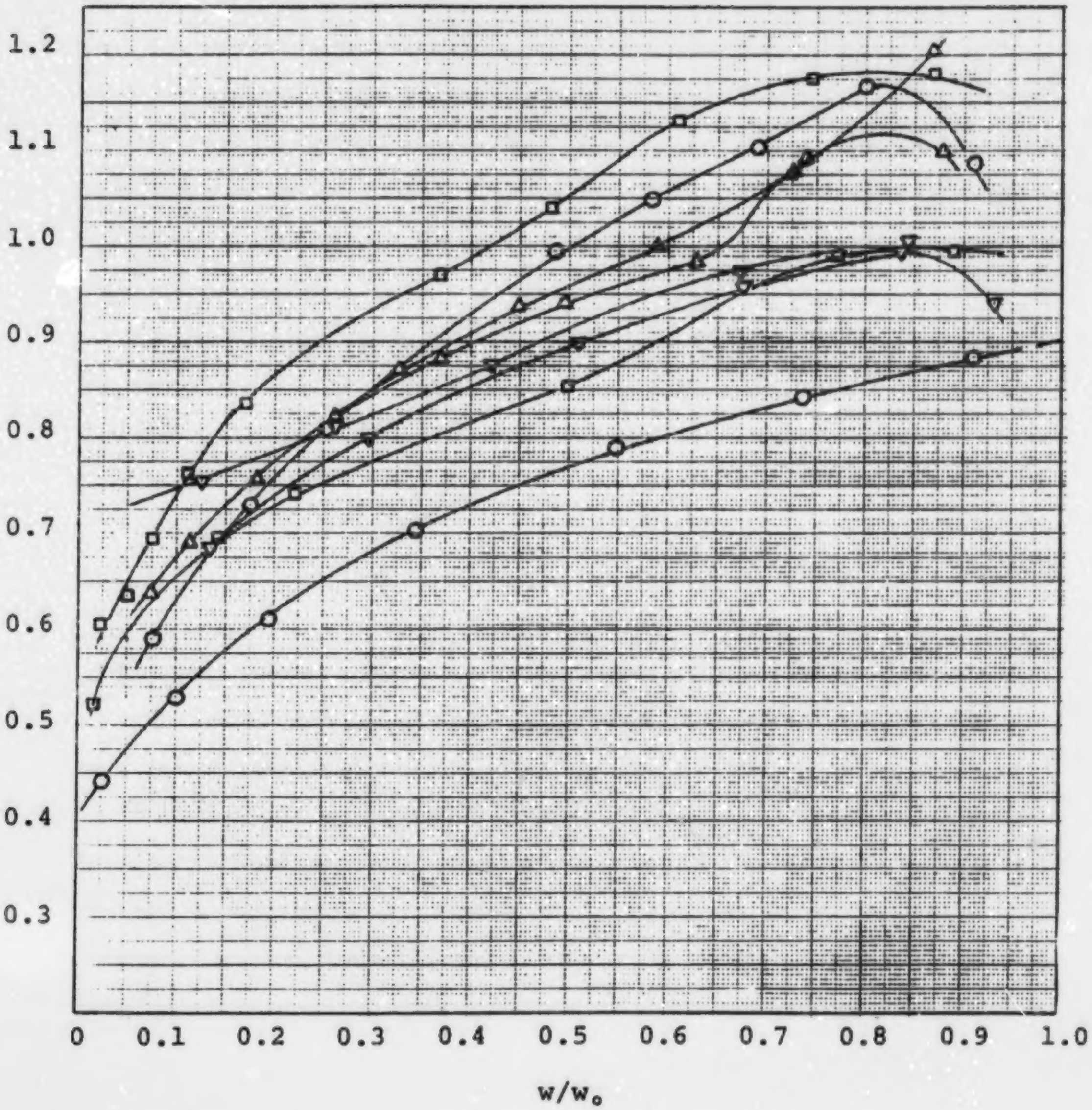


Fig. 22. Integral psychrometric drying efficiency as a function of reduced moisture content w.b. for drying maple chips with dry air. Key to symbols:

Inlet air temperature T_1, °C:	75	90	100	125
Symbol:	○	□	△	▽

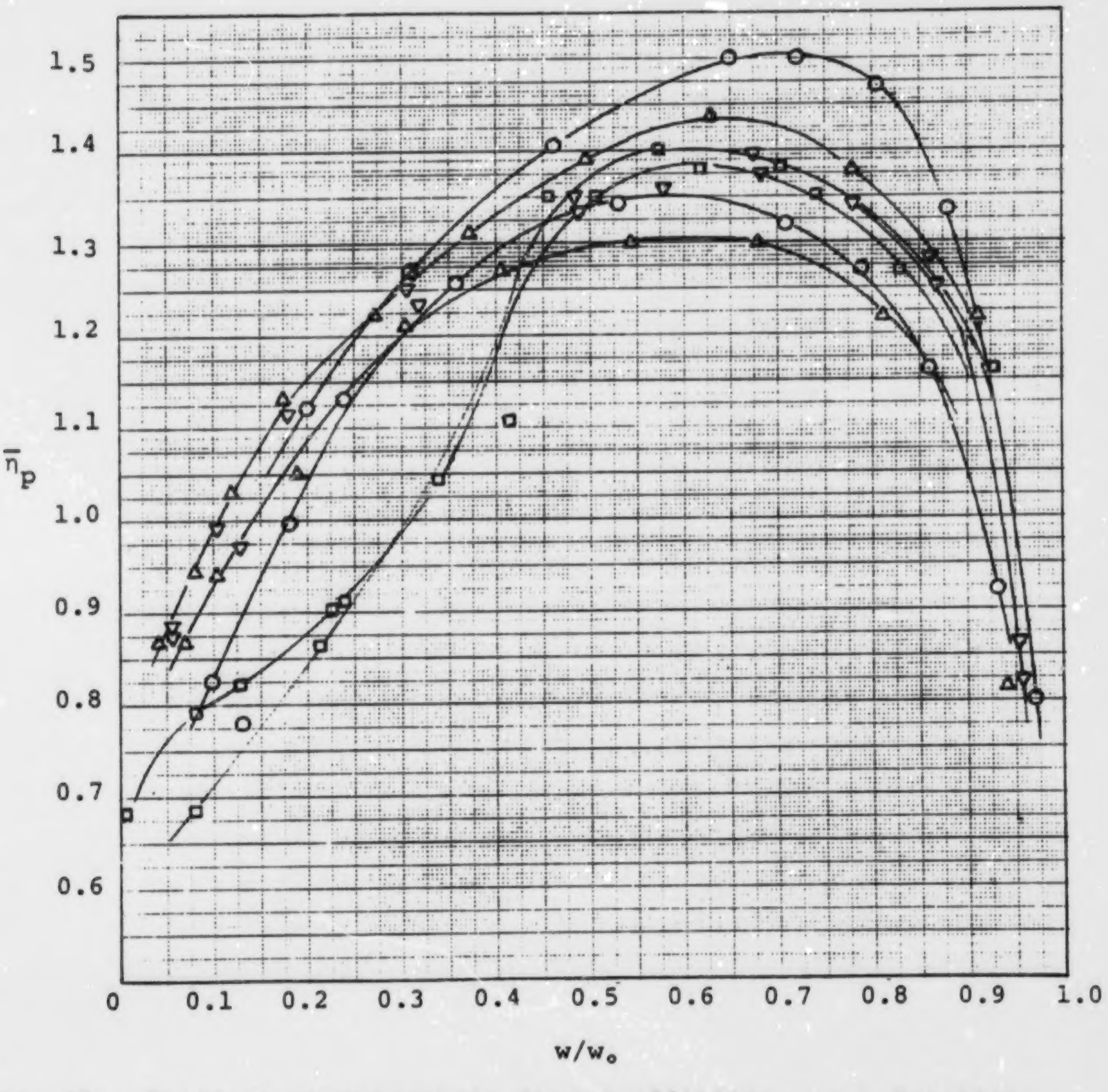


Fig. 23. Integral psychrometric drying efficiency as a function of reduced moisture content w.b. for drying maple chips with humid air. Key to symbols:

Inlet air temperature T_1, °C:	75	90	100	125
Symbol:	○	□	Δ	∇

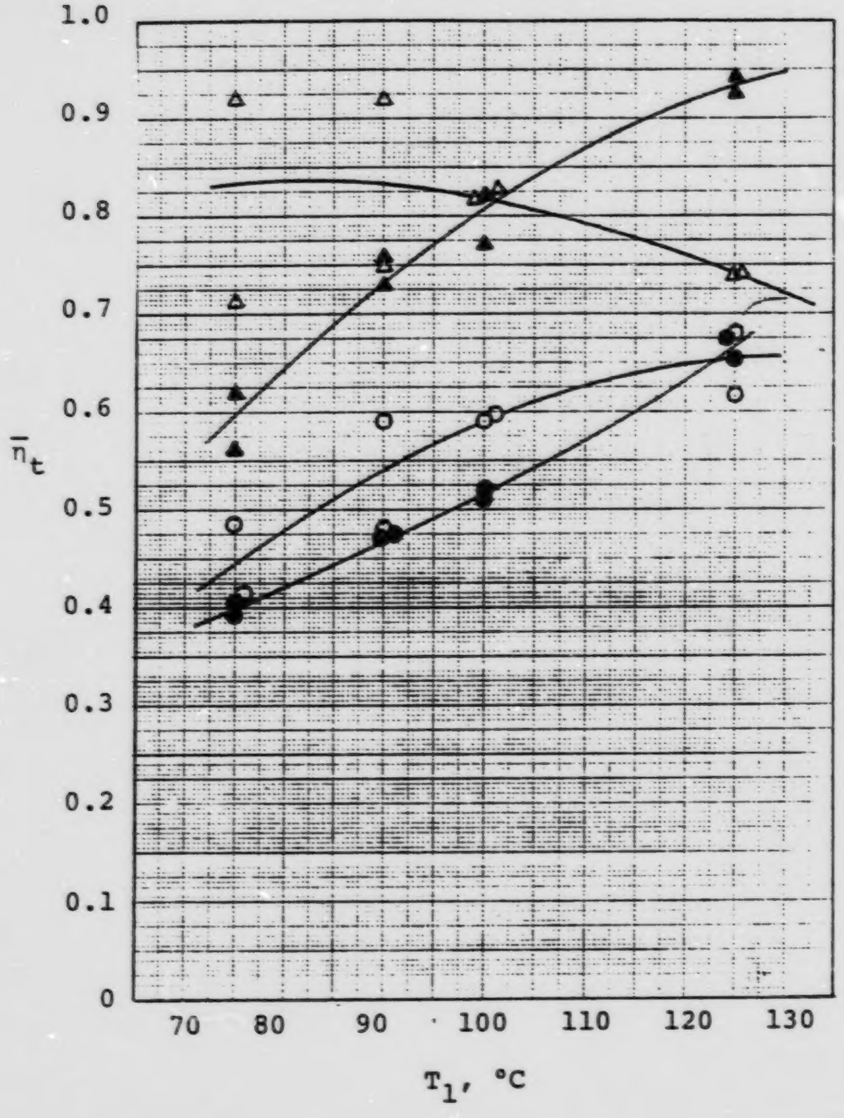


Fig. 24. Integral thermal drying efficiency at $w/w_o = 1/2$ as a function of inlet air temperature. Circles denote spruce chips, triangles maple, open symbols drying with dry air, shaded symbols drying with humid air.

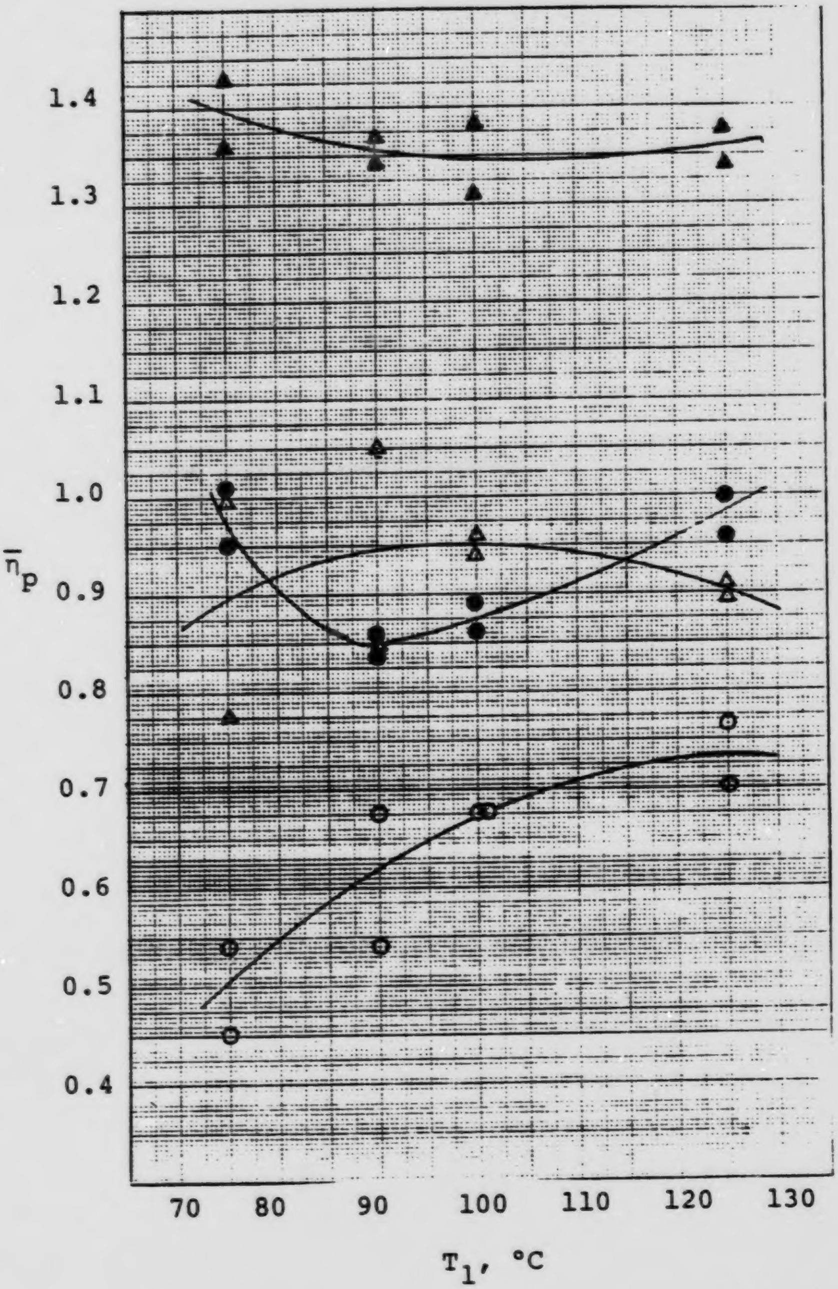


Fig. 25. Integral psychrometric drying efficiency at $w/w_o = 1/2$ as a function of inlet air temperature. Explanation of symbols: see Fig. 24.

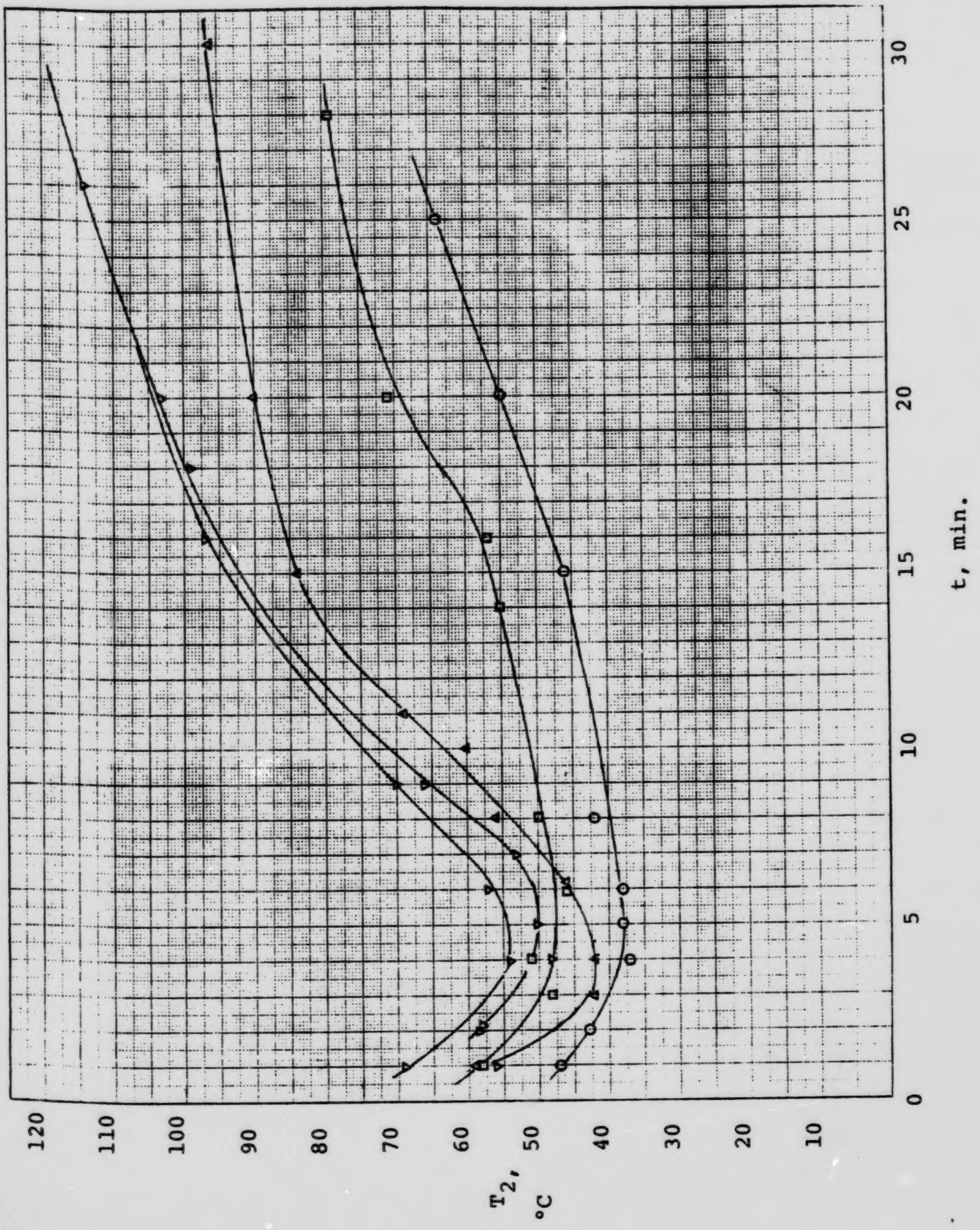


Fig. 26. Exit air temperature as a function of time in drying maple chips with dry air. Key to symbols:

Inlet air temperature, T_1, °C:	75	90	100	125
mbol:	○	□	△	▽

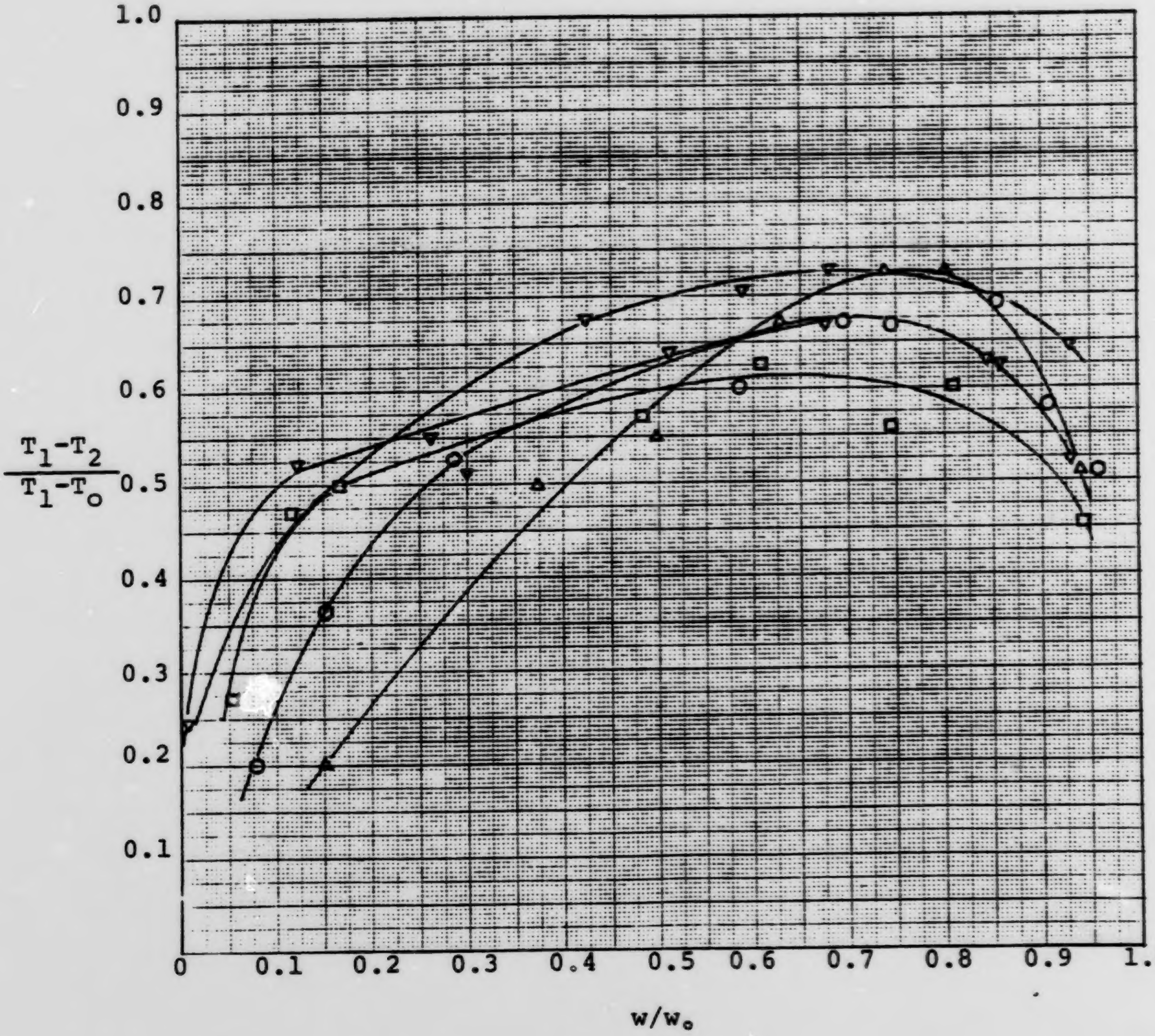


Fig. 27. Air temperature drop normalized on initial temperature driving force as a function of reduced moisture content w.b. in drying maple chips with dry air. Key to symbols:

Inlet air temperature T_1, °C:	75	90	100	125
Symbol:	○	□	△	▽

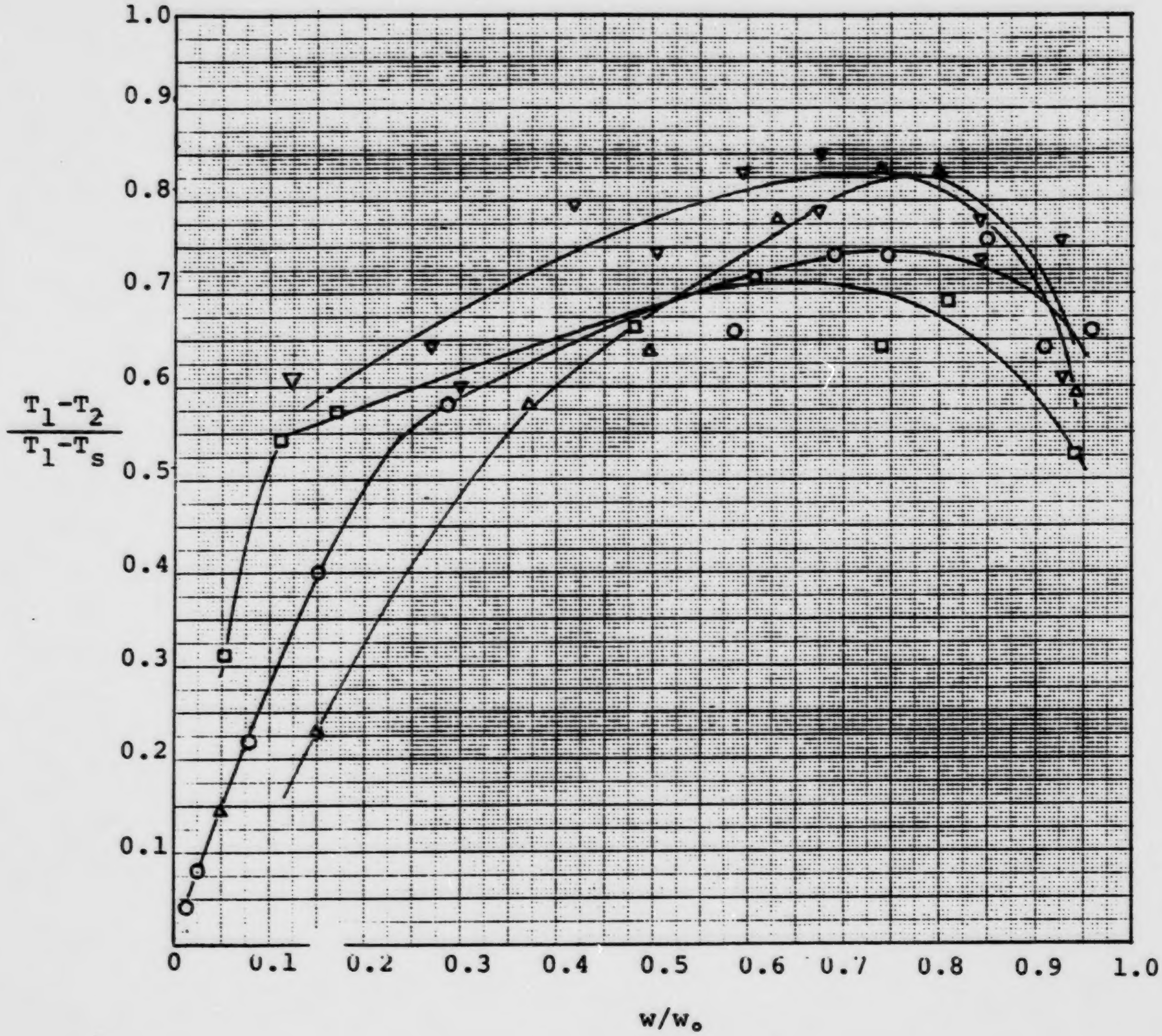


Fig. 28. Air temperature drop normalized on that for adiabatic saturation as a function of reduced moisture content w.b. in drying maple chips with dry air.

Inlet air temperature T_1, °C:	75	90	100	125
Symbol:	○	□	△	▽

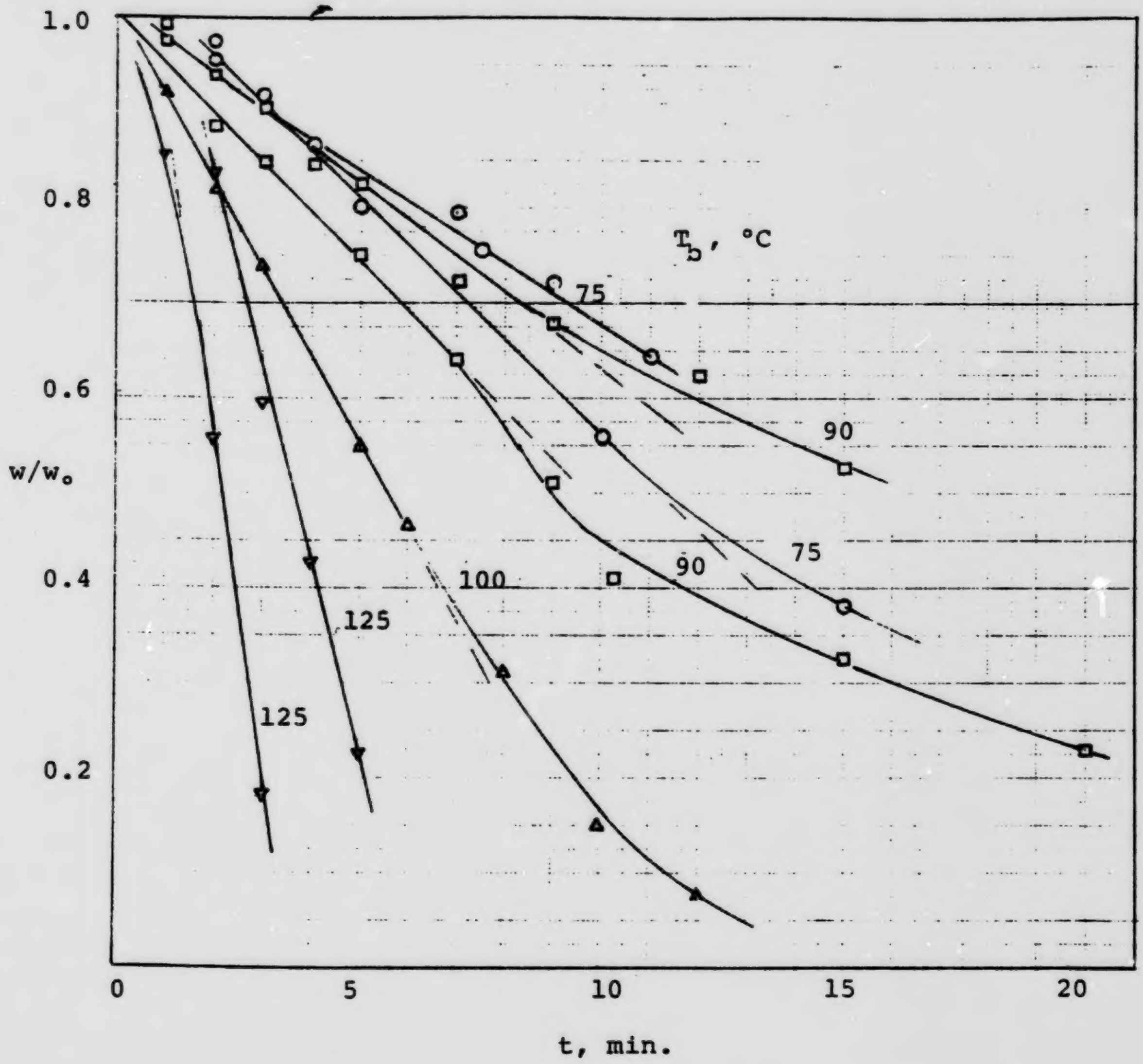


Fig. 29. Drying of single spruce chips with dry air in a fluidized bed sand bath: reduced moisture content w.b. vs. time with bath temperature as a parameter, initial moisture w_o = 0.43--0.51.

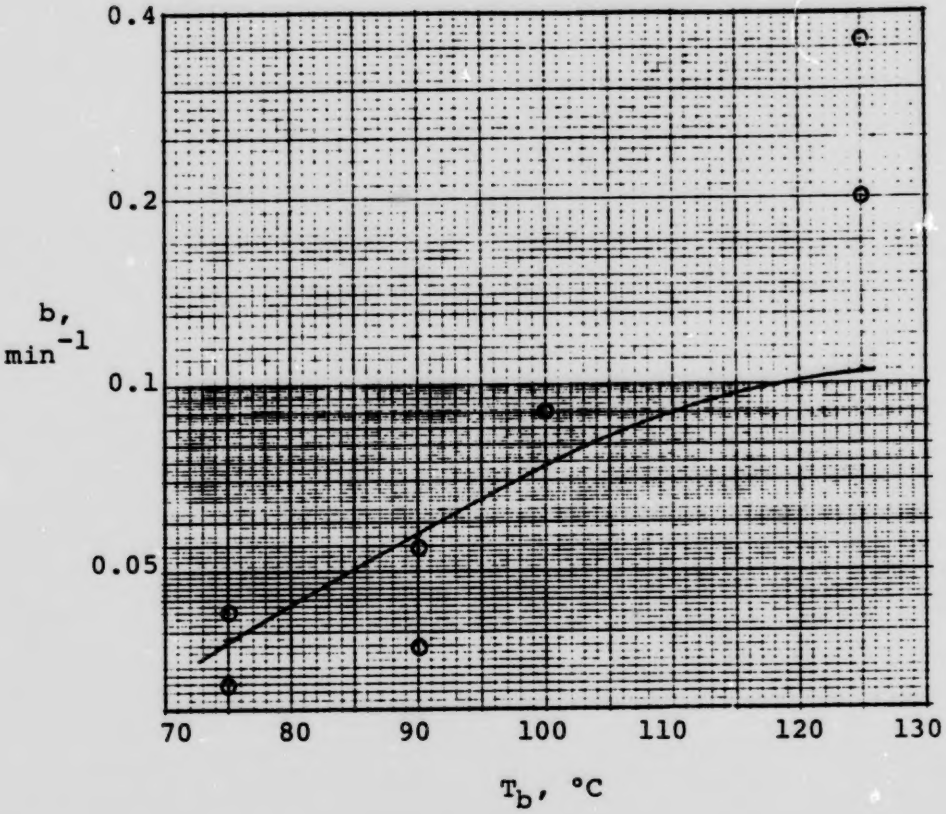


Fig. 30. Drying of single spruce chips with dry air in a fluidized bed sand bath: the coefficient b in the initial drying law $w/w_o = a - bt$ as a function of bath temperature. The curve represents the data in Fig. 10a for fixed-bed drying of spruce with dry air.

DSS File: 51SZ 23216-6-6177
July 16 1986
Page 1 of 1

APPENDIX "B"

DISCLOSURES CERTIFICATION

To be completed by you and submitted along with your final report to the Scientific Authority and the Science Procurement Officer.

CONTRACTOR: INTERTECH ENGINEERING CORPORATION

CONTRACT FILE NO.: 51SZ.23216-6-6177

CONTRACT SERIAL NO.: 23216-6-6177/01-SZ

X
Note 1: We certify that all applicable disclosures were submitted in compliance with DSS 9224 General Conditions Research and Development and in accordance with the INTELLECTUAL AND INDUSTRIAL PROPERTY clause of the contract.

OR

N/A We certify that there are no disclosures to submit in respect to DSS 9224 General Conditions Research and Development and in respect to INTELLECTUAL AND INDUSTRIAL PROPERTY clause of the contract.

Signature Robert Isles

Print Name Robert Isles

Title President

Company Name Intertech Engineering Corp.

Date September 1987

Note 1: Refer to Proprietory Rights reservations indicated on the following documents:

1 - Proposal letter dated Oct.21/85
Page 4 Item (viii) Clause 2

2 - Letter July 8/86

3 - Final Report Preface Section 1.4

APPENDIX D

A COMPUTER PROGRAMME
FOR
OPTIMIZATION OF A TREE CHIP DRYER

(CONSISTING OF 28 UNNUMBERED PAGES)

D: COMPUTER PROGRAMME

D.1 Purpose
D.2 Tabulation
D.3 Programme
D.4 Computer Simulation Test Results
D.5 Calculations of Dryer Performance
D.6 Illustration

D.1 Purpose of the Computer Programme

- To model the tree chip dryer system in order to verify the various energies being transferred in the regeneration drying.
- To determine the effects of varying certain conditions and changing certain parameters for evaluation of the dryer performance and cost analyses.

  These include:

  - physical features of the dryer eg. size of fans and condensers
  - flow rates of product through the system
  - conditions of the product
  - incoming ambient air dew point and dry bulb temperatures
  - heat output of the furnace.

D.2 TABULATION - Identifying the terms used in program and showing typical results.

TERMS IN DRYER PERF PGM	zone 0 (primary)	sec#1		sec#2		sec#3		sec#4		inlet or exh or total	
TEMPERATURES (°F)											
chips entering zone		tch1	212	tch2	98	tch3	86	tch4	58	tch5	
primary air entering zone		tcp1	212	tcp2	212	tcp3	158	tcp4	153	tph5	152
mixed sec air entering cdr		te1	134	te3	96	te3	99	te4	50		
sec air leaving condenser		tcd1	134	tcd2	96	tcd3	135	tcd4	50		
temp diff prim>sec at cdr		td1	n/a	td2	63	td3	35	td4	n/a		
sec air (avg) lvg chips		tlch1	125	tlch2	87	tlch3	82	tlch4	58		
air moving up to next zone		tmu1		tm2		tmu3		tmu4		ta tmu5	
air transferred to preheat		tph1	141	tph2	95	tph3	85	tph4	62	tph5	
air recirc in same zone		tr1	112	tr2	90	tr3	83	tr4	58		
MASS (lb/h)											
water in chips mw 5400	mw0 4862	mw1	3856	mw2	3763	mw3	3207	mw4	3034	mw5	
water evaporated	hfn 538	mev1	1006	mev2	93	mev3	556	mev4	173	tot	
condensate											
fan flow		ms1	16k	ms2	60k	ms3	60k	ms4	40k		
moving up to next zone		mmu1	8000	mmu2	12000	mmu3	16000	mmu4	28000		
to preheat zone		mph1	4000	mph2	4000	mph3	12000	mph4	12000		
recirculated		mr1	4000	mr2	44000	mr3	32000	mr4	0		
UNIT HEAT (but/lb)											
enthalpy of primary air in cdr		cp1		cp2	359	cp3	359	cp4	293	cp5	291
enth of sec air ent'g cdr		ee1	64	ee2	48	ee3	34	ee4	20		
enth of sec air lvg cdr		elcd1		elcd2		elcd3		elcd4			
enth of sec air lvg chips (avg)		elch1	127	elch2	50	elch3	344	elch4	24		
enth of air mvg up to next zone		emu1		emu2		emu3		emu4		emu5	
enth of air to preheat		eph1	104	eph2	50	eph3	44	eph4	24		
enth of air recirculated		er1	106	er2	50	er3	44	er4	--		
TOTAL HEAT (*1000)											
in air ent'g cdr prim		hcp1	2869	hcp2	2869	hcp3	2869	hcp4	2344	hcp5	
in air ent'g cdr sec		he1	1025	he2	2889	he3	2069	he4	800		
sup by condenser		hcd1	10	hcd2		hcd3		hcd4		tot	
in air lvg cdr		hlcd1	64	hlcd2	48	hlcd3	43	hlcd4	20		
sup by cooling		hc1	1006	hc2	93	hc3	31	hc4	173	tot	
in air lvg chips		hlch1	2031	hlch2	2982	hlch3	2625	hlch4	973		
moving up to next zone		hmu1	1190	hmu2	598	hmu3	702	hmu4	681		
to preheat		hph1	416	hph2	199	hph3	526	hph4	292	+2329	
useable amt to preheat		uph1	336	uph2	120	uph3	288	uph4	48		
recirc in same zone		hr1	425	hr2	2185	hr3	1397	hr4	0		

MISC--Conductivity of cdr, btu/lb/deg--c
mass of solids in chips--mch=6600, sp ht--shc=.6btu/lb/degF
mass of water in green chips, mw=5400, sp ht--shw=1 btu/lb/degF
sp ht of air with vapour = .24 btu/lb/degF, ht sup by furnace--hf=800 (*1000)

D.3 Program

This is a microcomputer program written in Amiga Basic using an Amiga personal computer.

Each equation used in the program determines the value of a single variable in terms of two or more other constants and variables. In each case, one or more of the values needed for an equation were still unknown. The program gets around this difficulty by assigning guestimates of all variables and subsequently iterating back and forth among the various equations until the numbers stabilized.

General Arrangement of Program

Lines 0 to Startcalc

Values are assigned to all constants and initial values assigned to all variables used in the program.

Startcalc to End

This section directs the calculations through two loops. The outer loop causes any chosen number of iterations of the complete inner loop. The inner loop directs the calculations to deal with the various energy and mass exchanges within one zone at a time. These deal with the four secondary heating and drying zones where the process is made complicated by recirculation flows with regenerative feedback of energy.

The happenings in the preheat zone and in the primary (furnace) drying zone have no recirculation and are readily calculable once the secondary effects are determined.

Within one zone at a time, the calculations are repeated by a number of times selected by observing the changing numbers on a monitor. Presently the sequence used is:

(3 x #4, 5 x #3, 10 x #2, 6 x #1, 10 x #2, 6 x #3), all x 5.

D.3 Program cont.

Heat in Secondary Air Leaving Condenser

This is a simple addition of heat entering plus heat transferred

h/cd4 = he4 + hcd4

Temperature of Air Leaving Condenser

tcd4 = te4 + hcd4/ms4/sha

The added temperature is calculated by dividing the heat by the mass of air and its specific heat.

Heat from Cooling

hc4 = (mw3 + mch x sha) x (tch4 = tch5)

All of the warm up heat is accounted for in the temperature of the finished chips and the water which leaves the system. The cooldown occurring at various stages in the dryer is counted in this equation in which the mass of water in the chips, plus the mass of solids multiplied by the temperature difference of the chips.

This cooldown heat is added to the heat leaving the condenser, to produce the total heat leaving the chips.

Separation of the Heat Leaving the Chips

The air which leaves the chips in each zone becomes split into three streams:

- heat moving up to next zone
- heat moving to preheat
- heat recirculated in same zone.

The difference in energy levels of these three streams are quite large because although the air going from the fan to the condenser secondary is mixed, the part which contacts the highest temperature of the condenser primary will also contact the highest temperature of the chips.

D.3 Program cont.

It is assumed that the enthalpy being added in these two exchanges will be proportional to the 90% humidity enthalpies of the air at the temperature where it leaves the chips, and that these air temperatures will be the same as the chip temperatures where the air leaves the chips.

Temperatures of the air leaving the chips are calculated by subtracting a ratio of the temperature range from the top temperature of the range.

For instance, the ratio used for preheat temperature is

rsph = (.5 x mph4 + mmu4)/ms4,

calculated among the constants in the initialization of the program.

The enthalpies calculated from temperatures and the psychrometric program do not initially balance with the total heat calculated by additions of entering heat plus heat from condenser and heat from cooling.

The ratio r corrects for this imbalance

r = hlch4/(hmu4 + hph4 + hr4)

The heat added in individual streams is multiplied by r to make the total balance the actual heat added.

It is assumed that part of the furnace energy will be used for topping up the chip temperature to the boiling point. This effect is shown by the equation

mev0 = hf x (1 - (212 - tph 1)x(mc x sha + mw))

If the rate of evaporation in the primary drying zone is so rapid that the temperature of the chips stays below the boiling point, then all secondary temperatures will be a little lower than previously figured, but there will be increased enthalpy in the primary of the condenser. These effects will almost balance one another in affecting the total amount of evaporation but the higher temperatures are desirable for faster drying. Since we cannot predict in advance how much heating of chips occurs in the primary drying, it is important to raise the chip temperature as high as possible in the preheat zone.

D.3 Program cont.

```
 n this version t1=0 and c1=15000.
09:05:10

3-21-1987 09:07:08  ANALYSIS OF TREE CHIP DRYER. ver.3+0
fan flows.lb/h  8000  16000  60000  60000  40000
temp.amb.air  50    furnace ht  800   Conductivity of cdr.btu/h/degF  5000
mass of water evap=  2686    coef of perf=  3.3575
usable to preheat= 1868.855
mass of green chips.init water 12000  5400   final mc .2913893
 REM ITERATIVE CALCULATIONS OF CHIP DRYER PERF. ON AMIGA COMPUTER. mar4/87
  CLS:DEFINT e,t,v,c,h,n'   -----ver.3+0.mar21/87

const: c=5000'  btu/h/deg in cdr
  ta=50:ea=20:tmu5=ta:emu5=ea  temp & enth air
  tcp1=212:tch1=212'  degF prim & chips ent sec#1
  ms1=16000&:ms2=60000&:ms3=60000&:ms4=40000&   fan flows
  mph1=4000:mph2=4000:mph3=12000:mph4=12000&  mass to preheat
  mmu5=45000&:mmu4=28000&:mmu3=16000:mmu2=12000:mmu1=8000:mc=mmu1
  mr4=ms4-mmu4-mph4:mr3=ms3-mmu3-mph3:mr2=ms2-mmu2-mph2:mr1=ms1-mmu1-mph1
  r1mu=.5*mmu1/ms1:r1ph=(.5*mph1+mmu1)/ms1:r1r=(.5*mr1+mph1+mmu1)/ms1
  r2mu=.5*mmu2/ms2:r2ph=(.5*mph2+mmu2)/ms2:r2r=(.5*mr2+mph2+mmu2)/ms2
  r3mu=.5*mmu3/ms3:r3ph=(.5*mph3+mmu3)/ms3:r3r=(.5*mr3+mph3+mmu3)/ms3
  r4mu=.5*mmu4/ms4:r4ph=(.5*mph4+mmu4)/ms4:r4r=(.5*mr4+mph4+mmu4)/ms4
  mchg=12000:moist=.45:mw=mchg*moist:mch=mchg-mw   lb/h.green chips.water.solids
  shc=.6:shw=1:sha=.24' sp ht of chips.water and air
  hf=800 : hchu=(mch*shc+mw)*(tch1-ta)/1000    furn ht
var:
  mw0=mw-800:mw1=mw0-400:mw2=mw1-500:mw3=mw2-500:mw4=mw3-500  rem.water lvg zone
  tcp2=170:tcp3=165:tcp4=150:tcp5=100    sat p air ent cdr
  hcp2=2000:hcp3=1600:hcp4=1000'  ht in cdr prim
  tch2=150:tch3=115:tch4=87:tch5=74   avg t chips ent
  ta1=175:ta2=140:te3=105:te4=70   t ent cdr
  tcd1=175:tcd2=150:tcd3=132:tcd4=90   temp lvg cdr
  td1=8:td2=25:td3=41:td4=68'  t diff cdr
  tich1=160:tich2=101:tich3=85:tich4=69'  avg t of air lvg chips
  tmu1=180:tmu2=160:tmu3=135:tmu4=100   t moving up to next
  enth1=hcp1+1000/mp:enth2=hcp2*1000/mp:enth3=hcp3*1000/mc:enth4=hcp4*1000/mp   enth in prim
 cdr
  he1=10000:he2=6000:he3=2000:he4=1500   ht ent cdr

STARTCALC: LPRINT TIME$
```

D.3 Program cont.

```
STARTCALL: LPRINT TIME$
  GOSUB view
outerloop: FOR n5=1 TO 5:LOCATE 1.1:PRINT n5:
n4: n4=0
n4plus1: GOSUB calc4:n4=n4+1
LOCATE 22.69:PRINT n4:
  IF n4<5 THEN n4plus1
n3: n3=0
n3plus1: n3=n3+1
LOCATE 22.59:PRINT n3:
GOSUB calc3
IF n3<5 THEN n3plus1
n2: n2=0
n2plus1: n2=n2+1
LOCATE 22.49:PRINT n2:
GOSUB calc2
IF n2<5 THEN n2plus1
n1:n1=0
n1plus1: n1=n1+1
LOCATE 22.39:PRINT n1:
GOSUB calc1
IF n1<5 THEN n1plus1
n21:n2=0
n21plus1:n2=n2+1
LOCATE 22.49:PRINT n2:
GOSUB calc2
IF n2<5 THEN n21plus1
n31:n3=0
n31plus1:n3=n3+1
LOCATE 22.59:PRINT n3:
GOSUB calc3
IF n3<5 THEN n31plus1
nextz: NEXT n5
GOSUB printr
END:END


calc4:
```

INTERTECH ENGINEERING CORPORATION

D.3 Program cont.

```
ta.t4:
  IF tco4<tcd4 THEN tco4=tcd4+1
  IF tco5<te4 THEN tco5=te4+1
  x=td4:v=SQR((tco4-tcd4)*(tco5-te4)):td4=(x+v)/2:IF td4<100 THEN td4=100
LOCATE 22.64:PRINT td4
  z=nco4:hco4=0*td4/1000:t=tco4:GOSUB entn.:eco4=e
  nco4=nco4+z-hco4:eco4=nco4*1000/mo:e=eco4:GOSUB temp.9:tco4=t
  eco5=eco4-hco4*1000/mo:e=eco5:GOSUB temp1:tco5=t
  nco5=nco4-hco4:uco5=nco5*(eco5-emu5)/eco5
LOCATE 23.72:PRINT INT(uco5):
LOCATE 2.72:PRINT tco5:
LOCATE 13.64:PRINT INT(nco4):
  nico4=he4+nco4:eico4=nico4*1000/ms4
  tcc4=te4+hcc4*1000/ms4/sha
LOCATE 8.64:PRINT tco4:
  x=nc4:v=(mw3+mcn*snc)/1000*(tcn4-tcn5):nc4=(x+v)/2:nicn4=nico4+nc4
  eicn4=nc4*1000/ms4+ee4:e=eicn4:GOSUB temp.9:tcn5=t
  mw4=mw3-nco4-nc4:mev4=nco4+nc4
  nch4=(tcn5-ta)*(mw4+snc*mcn)/1000
LOCATE 11.64:PRINT INT(mw4):

LOCATE 14.64:PRINT INT(nc4):
LOCATE 15.64:PRINT INT(hicn4):
  eicn4=nicn4*1000/ms4:e=eicn4: GOSUB temp.9:ticn4=t
LOCATE 16.64:PRINT eicn4:
LOCATE 4.64:PRINT ticn4:
  tmu4=(tmu4+tcn4-.5*(tcn4-tcn5)*mmu4/ms4)/2
LOCATE 5.64:PRINT tmu4:
  trange=tcn4-tcn5:tmu4=tcn4-r4mu*trange
  t=tmu4:GOSUB entn.9:emu4=(e*eicn4)^.5:nmu4=emu4*mmu4/1000
  ton4=tcn4-r4on*trange
  t=ton4:GOSUB entn.9:eon4=(e*eicn4)^.5:non4=eon4*mon4/1000
  tr4=tcn4-r4r*trange
  t=tr4:GOSUB entn.9:er4=(e*eicn4)^.5:nr4=er4*mr4/1000
  r=(hcd4+nc4)/(nmu4+non4+nr4):nmu4=nmu4*r+ne4*mmu4/ms4
  non4=hon4*r+ne4*mon4/ms4:nr4=nr4*r+ne4*mr4/ms4
  emu4=nmu4*1000/mmu4:eon4=non4*1000/mon4:er4=0
  te4=ta
LOCATE 9.64:PRINT te4:
LOCATE 17.64:PRINT emu4:
LOCATE 19.64:PRINT er4:
LOCATE 7.64:PRINT tr4:
LOCATE 20.64:PRINT INT(nmu4):
LOCATE 6.64:PRINT ton4:
LOCATE 18.64:PRINT eon4:
  uon4=(eon4-ea)*mon4/1000
LOCATE 23.64:PRINT INT(uon4):
  mr4=0
LOCATE 10.64:PRINT INT(mr4):
LOCATE 21.64: PRINT INT(nr4):
  ne4=ms4*ea/1000:ee4=ea
LOCATE 12.64:PRINT INT(ne4):
LOCATE 3.72:PRINT tcn5:
r4:RETURN
```

D.3 Program cont.

```
 ta.c3:
   IF tco3<tcd3 THEN tco3=tcd3+1
   IF tco4<te3 THEN tco4=te3+1
   x=td3:v=SQR((tco3-tcd3)*(tco4-te3)):td3=(x+v)/2
 LOCATE 22.54:PRINT td3:
   z=hcd3:hcd3=15000*td3/1000
   eco4=eco3-hcd3/mo*1000:e=eco4:GOSUB temp1:tco4=t
   hco4=hco3-hcd3
 LOCATE 2.64:PRINT tco4:
 LOCATE 13.54:PRINT INT(hcd3):
   hicd3=he3+hcd3:eicd3=hicd3/ms3*1000
   tco3=te3+hcd3*1000/ms3/sha
 LOCATE 8.54:PRINT tco3:
   x=hc3:v=(mw2+mch*shc)/1000*(tch3-tch4):hc3=(x+v)/2
   hich3=hicd3+hc3:mw3=mw2-(hcd3+hc3)
   mw3=mw2-hcd3-hc3:mev3=hcd3+hc3
   hch3=(tch4-ta)*(mw3+shc*mch)/1000
 LOCATE 11.54:PRINT INT(mw3)
 LOCATE 14.54:PRINT INT(hc3):
 LOCATE 15.54:PRINT INT(hich3):
   eich3=hich3*1000/ms3:e=eich3: GOSUB temp.9:tich3=t
 LOCATE 16.54:PRINT eich3:
 LOCATE 4.54:PRINT tich3:
   tmu3=(tmu3+tch3-.5*(tch3-tch4)*mmu3/ms3)/2
 LOCATE 5.54:PRINT tmu3:
   trange=tch3-tch4
   tmu3=tch3-r3mu*trange
   t=tmu3:GOSUB enth.9:emu3=(e*eich3)^.5:hmu3=emu3*mmu3/1000
   ton3=tch3-r3on*trange
   t=toh3:GOSUB enth.9:eon3=(e*eich3)^.5:hon3=eon3*mon3/1000:uon3=hon3-(mon3*eon4)
   tr3=tch3-r3r*trange
   t=tr3:GOSUB enth.9:er3=(e*eich3)^.5:hr3=er3*mr3/1000
   r=(hcd3+hc3)/(hmu3+hon3+hr3):hmu3=hmu3*r+he3*mmu3/ms3
   hoh3=hon3*r+he3*mon3/ms3:hr3=hr3*r+he3*mr3/ms3
   emu3=hmu3*1000/mmu3:eon3=hon3*1000/mon3:er3=hr3*1000/mr3
   te3=(te3+(tr3*mr3+tmu4*mmu4)/(mr3+mmu3))/2
 LOCATE 9.54:PRINT te3:
 LOCATE 17.54:PRINT emu3:
 LOCATE 19.54:PRINT er3
 LOCATE 20.54:PRINT INT(hmu3):
 LOCATE 6.54:PRINT ton3:
 LOLATE 7.54:PRINT tr3:
 LOCATE 18.54:PRINT eon3:
   uon3=(eon3-emu5)*mon3/1000
 LOCATE 23.54:PRINT INT(uon3):
   mr3=ms3-mmu3-mon3-mex3
 LOCATE 10.54:PRINT INT(mr3):
 LOCATE 21.54: PRINT INT(hr3):
   he3=hr3+(ms3-mr3)*emu4/1000:ee3=he3/ms3*1000
 LOCATE 12.54:PRINT INT(he3):
   e=eicd3:GOSUB temp.9:tch4=(tch4+t)/2
 LOCATE 3.64:PRINT tch4:
 r3:RETURN
```

D.3 Program cont.

```
ta:c2:
  tc2=0
LOCATE 22.44:PRINT tc2:
  t=tco2:GOSUB enth1:eco2=e
  hco2=hco1:eco2=hco2*1000/mo
  eco3=eco2:tco3=tco2' when c=0
  hco3=hco2
LOCATE 2.54:PRINT tco3:
LOCATE 13.44:PRINT INT(hco2):
  hlcd2=he2:elcd2=hlcd2*1000/ms2
  tcd2=te2
LOCATE 8.44:PRINT tcd2:
  x=hc2:v=(mw1+mch*shc)/1000*(tch2-tch3):hc2=(x+v)/2
  hlch2=hlcd2+hc2:mw2=mw1-hco2-hc2:mev2=hco2+hc2
  hch2=(tch3-ta)*(mw2+shc+mch)/1000
LOCATE 11.44:PRINT INT(mw2):
LOCATE 14.44:PRINT INT(hc2):
LOCATE 15.44:PRINT INT(hich2):
  eich2=hich2*1000/ms2:e=eich2: GOSUB temp.9:tich2=t
LOCATE 16.44:PRINT eich2:
LOCATE 4.44:PRINT tich2:
  tmu2=(tmu2+tch2-.5*(tch2-tch3)*mmu2/ms2)/2
LOCATE 5.44:PRINT tmu2:
  trange=tch2-tch3
  tmu2=tch2-r2mu*trange
  t=tmu2:GOSUB enth.9:emu2=(e*eich2)^.5:hmu2=emu2*mmu2/1000
  toh2=tch2-r2oh*trange
  t=toh2:GOSUB enth.9:eoh2=(e*eich2)^.5:hoh2=eoh2*moh2/1000:uoh2=hoh2-(moh2*eoh3)
  tr2=tch2-r2r*trange
  t=tr2:GOSUB enth.9:er2=(e*eich2)^.5:hr2=(hr2+er2*mr2/1000)/2
  r=(hcd2+hc2)/(hmu2+hoh2+hr2):hmu2=hmu2*r+he2*mmu2/ms2:hoh2=hoh2*r+he2*moh2/ms2
  hr2=hr2*r+he2*mr2/ms2
  emu2=hmu2*1000/mmu2:eoh2=hoh2*1000/moh2:er2=hr2*1000/mr2
  t=(tr2*mr2+tmu3*mmu3)/(mr2+mmu2):te2=(t+te2)/2
LOCATE 9.44:PRINT te2:
LOCATE 17.44:PRINT emu2:
LOCATE 19.44:PRINT er2:
LOCATE 20.44:PRINT INT(hmu2):
LOCATE 6.44:PRINT toh2:
LOCATE 7.44:PRINT tr2:
LOCATE 18.44:PRINT eoh2:
  uoh2=(eoh2-emu5)*moh2/1000
LOCATE 23.44:PRINT INT(uoh2):
  mr2=ms2-mmu2-moh2
LOCATE 10.44:PRINT INT(mr2):
LOCATE 21.44: PRINT INT(hr2):
  he2=hr2+(ms2-mr2)*emu3/1000:ee2=he2/ms2*1000
LOCATE 12.44:PRINT INT(he2):
  e=elcd2:GOSUB temp.9:tch3=(tch3+t)/2
LOCATE 3.54:PRINT tch3:
r2:RETURN
```

D.3 Program cont.

```
calc1:
LOCATE 2.34:PRINT tco1:
LOCATE 3.34:PRINT tcn1:
LOCATE 22.34:PRINT "nil":
  hco2=nco1:eco2=eco1:tco2=tco1:nco1=0:tco1=ta
LOCATE 2.44:PRINT tco2:
LOCATE 13.34:PRINT "nil":
  nicd1=nel:eicd1=nicd1*1000/msl
LOCATE 8.34:PRINT tcd1:
  ncl=(mw0+mcn*snc)/1000*(tch1-tcn2)
  hich1=nel+hcl:mw1=mw0-ncl:mevi=ncl
  nch1=(tch2-ta)*(mw1+snc*mcn)/1000
LOCATE 11.34:PRINT INT(mw1):
LOCATE 14.34:PRINT INT(ncl):
LOCATE 15.34:PRINT INT(nich1):
  eicn1=nicn1*1000/msl:e=eicn1: GOSUB temp.9:ticn1=t
LOCATE 16.34:PRINT eicn1:
LOCATE 4.34:PRINT ticn1:
  tmu1=(tmu1+tch1-.5*(tch1-tcn2)*mmu1/msl)/2
LOCATE 5.34:PRINT tmu1:
  trange=tcn1-tcn2
  tmu1=tch1-rlmu*trange
  t=tmu1:GOSUB entn.9:emu1=(e*eicn2)^.5:nmu1=emu1*mmu1/1000
  tohl=tcn1-rloh*trange
  t=tohl:GOSUB entn.9:eohl=(e*eicn2)^.5:nohl=eohl*mohl/1000
  trl=tcn1-rlr*trange
  t=trl:GOSUB entn.9:erl=(e*eicn1)^.5:nrl=(nrl+erl*mrl/1000)/2
  r=ncl/(hmu1+hohl+hrl):hmu1=hmu1*r+nel*mmu1/msl:hohl=hohl*r+nel*mohl/msl
  hrl=hrl*r+hel*mrl/msl
  hfn=nf-(tco1-tmu1)*(mcn*snc+mw)/1000:nco1=nmu1+nfn+mev0*(tco1-ta):mw0=mw-nfn
  emu1=hmu1*1000/mmu1:eohl=hohl*1000/mohl:erl=hrl*1000/mrl
  t=(trl*mrl+tmu2*mmu2)/(mrl+mmu1):tel=(t+tel)/2
LOCATE 9.34:PRINT tel:
LOCATE 17.34:PRINT emu1:
LOCATE 19.34:PRINT erl:
LOCATE 20.34:PRINT INT(hmu1):
LOCATE 6.34:PRINT tohl:
LOCATE 7.34:PRINT trl:
LOCATE 18.34:PRINT eohl:
  uohl=(eohl-emu5)*mohl/1000
LOCATE 23.34:PRINT INT(uohl):
  mrl=msl-mmu1-mohl
LOCATE 10.34:PRINT INT(mrl):
LOCATE 21.34: PRINT INT(nrl):
  hel=hrl+(msl-mrl)*emu2/1000:eel=hel/msl*1000
LOCATE 12.34:PRINT INT(hel):
  e=elcd1:GOSUB temp.9:tcn2=(tcn2+t)/2
LOCATE 3.44:PRINT tcn2:
r1:RETURN
```

```
print": LPRINT
mev=mev1+mev2+mev3+mev4+ht+:perf=mev/ht
uph=uph1+uph2+uph3+uph4+uph5
LPRINT" DATE$:" ":TIME$:"  ANALYSIS OF [illegible] CHIP DRYER. VER.1+0"
LPRINT "fan flows.lb/h ":mc:ms1:ms2:ms3:ms4
LPRINT "temp.amb.air ":ta:"   furnace ht ":ht:"  conductivity of cdr.btu/h/degr  ":c
LPRINT "mass of water evap= ":
LPRINT mev:
LPRINT "   coef of perf= ":perf
LPRINT"useable to preheat=":
LPRINT uph
LPRINT"mass of green chips.init water":mcng:mw:"  final mc":(mw-mev)/(mcng-mev)
RETURN
view:
LOCATE 1.6:PRINT "ZONES----->";:PRINT TAB(24)"SEC#1";:PRINT  TAB(44)"SEC#2";:PRINT TAB(54)"S
EC#3
":TAB(64)"SEC#4":TAB(72)"EXH"
LOCATE 2.1:PRINT"temp prim air ent cdr":
LOCATE 3.1:PRINT "temp chips entering zone":
LOCATE 4.1:PRINT "temp avg air lvg chips":
LOCATE 5.1:PRINT "temp.air moving to next zone":
LOCATE 6.1:PRINT "temp.air moving to preheat":
LOCATE 7.1:PRINT "temp.air recirc in same zone":
LOCATE 8.1:PRINT "temp.avg sec air lvg cdr":
LOCATE 9.1:PRINT "temp.air ent.cdr":
LOCATE 10.1:PRINT "recirc flow at fan":
LOCATE 11.1:PRINT "liquid rem in chips":
LOCATE 12.1:PRINT "heat in sec air entering cdr":TAB(72)"*1000"
LOCATE 13.1:PRINT "heat sup by condenser":
LOCATE 14.1:PRINT "heat from chip cooling":
LOCATE 15.1:PRINT "heat leaving the chips":
LOCATE 16.1:PRINT "avg enth lvg chips":
LOCATE 17.1:PRINT "enthalpy mvg up to next zone":
LOCATE 18.1:PRINT "enthalpy entering preheat":
LOCATE 19.1:PRINT "enthalpy recirculated":
LOCATE 20.1:PRINT "heat moving up a zone":
LOCATE 21.1:PRINT "heat recirculated in same zone":
LOCATE 22.1:PRINT "temp diff at cdr":
LOCATE 23.1:PRINT "useable ht to ph":
11000 RETURN

temp.9:
  IF e>30.17 THEN 31
  IF e<20 THEN t=51 ELSE IF e<21.09 THEN t=52 ELSE IF e<21.65 THEN t=53 ELSE IF e<22.22 THEN
 t=5
4
  IF e<=22.2 THEN 2000
  IF e<22.8 THEN t=55 ELSE IF e<23.4 THEN t=56 ELSE IF e<24 THEN t=57 ELSE IF e<24.62 THEN t
=58
  IF e<=24.62 THEN 2000
  IF e<25.62 THEN t=59 ELSE IF e<25.9 THEN t=60 ELSE IF e<26.56 THEN t=61 ELSE IF e<27.23 TH
EN t
=62
  IF e<=27.23 THEN 2000
  IF e<27.92 THEN t=63 ELSE IF e<28.62 THEN t=64 ELSE IF e<29.34 THEN t=65 ELSE IF e<=30.17
THEN
 t=66
31 IF e<30.17 THEN 2000 ELSE IF e>48.83 THEN 51
```

Psychrometric subroutines continue for several pages.

D.6 Illustration

Illustration of the Kind of Calculations used in Computer Analysis of Chip Dryer

PREHEATING
6 t/h wet chips = 6 x 2204 lb/h = 13224 lb.
moisture 40% wet basis = 5290 lb.
solids 60% wet basis = 7934 lb.
sp ht of dry wood = .50 btu/°F/lb.
sp ht of moisture content = 1
ambient temperature = 50 °F
desired preheat temperature = 200°F

preheat required = (200-50)x(7934 x .5 + 5290 x 1)-------(1)
= 1483050 btu/h

SECONDARY DRYING
Heat from condenser
entering primary temperature = 200
leaving " " = 160
highest secondary entering temperature = 160
lowest " " " = 60 Avg. = 110
highest secondary leaving temperature = 180
lowest " " " = 100 Avg. = 140

temperature difference td = sq.rt. of (200-140)x(160-110)
= 55(°F)

overall conductivity of condenser = 30,000 btu/deg
(from conductivity program)
heat transferred from condenser = 29,000x55 = 1,595,000 btu/h

Heat from cooling of chips and residual water
chips mass = 7934 lbs.
sp ht = .5
end temperature = (lowest condenser inlet t + 4
+ lowest condenser outlet t)/2
= (60 + 4 + 100)/2 = 82
heat = 7934 x .5*(200-82) = 468,106 btu/h

Remark --- Chips leaving at the bottom of the conveyor will be at The lowest temperature of the condenser secondary exit, those at the top will be at the temperature of the lowest part of the return air from the chip drying, which is a few degrees above the temperature of the condenser entering air.

remaining water in chips, 25%(wet basis) = 2644 lbs.
heat = 2644 x 1 x (200-82) = 311,992 btu/h

D.6 Illustration cont.

The vapour which is evaporated from secondary drying and goes to preheat will amount to 1000 lb/h at various evaporation temperatures averaging far below the average temperature of aair leaving the secondary drying, say at 120°F. This water is cooled from 200° before it evaporates. Heat transferred to secondary drying by this cooldown = 1000 x (200-120) = 80,000 btu/h.

total heat from coold'g of chips and water =
468,106 + 31,992 + 80,000 = 860,098 btu/h.

Total sensible heat produced in secondary of dryer =
1,595,000 + 860,098 = 2,455,000
(which is sufficient to evaporate 2,455 lbs. of water/hr)

Disposition of secondary heat after drying chip with it

35% to preheat------------------------859,00 btu/h

with mass flow of 60,000 lb. air/h, 14.3 btu/lb. added to 20 btu/lb. in ambient air = 34.3 btu/lb. From psychrometric table for 90% rh, this occurs at an average temperature of 72°F. Actually there will be a number of different temperatures in the air to the preheat, with a very large flow at the lowest temperature and a very small flow carrying 25% of this energy at the top temperature. The computer program, which differentiates between four secondary zones will make this clear.

65% to furnace and primary--------1,596,000 btu/h

To carry this heat in 3000 lb/h of air, as used in the calculations of condenser capacity, requires 532 btu/lb., which corresponds to a temperature of 172°F in air at 90% rh coming off the chips in the part of the secondary drying closest to the primary drying. This temperature will probably be higher than 172° with the r.h. could lower than 90%.

PRIMARY OF CONDENSER

heat added by furnace = 800,000 btu/h
total heat entering primary of condenser = 2,396,00 btu/h
in 3000 lb/h this is 799 btu/lb., which corresponds to a temperature of 181°F. The actual temperature will be 212°F.

subtracting the 1,595,0 btu/h transferred to the secondary leaves 801,000 btu/h at the bottom of the primary, for transfer to the preheat at an enthalpy of 267 btu/lb. and temperature of 151°F.

D.6 Illustration cont.

Total heat transferred to the preheat is 801,000 + 859,000 = 1,660,000 btu/h, which moderately exceeds the 1,483,000 btu/h calculated to be needed.

This temperature is lower than the 160° assumed in the condenser heat transfer calculations, but it is getting close. This kind of result is the reason why these calculations require the many iterations, which are possible in a computer program.

I think that the calculations so far are sufficient to show that these numbers are fairly close to reality. In the next iteration, we would assume a lower final temperature in the primary of the condenser, resulting in a smaller heat transfer to the secondary, and a smaller quantity of heat transferred to the preheat from the primary.

Evaporation
      from furnace heat of 800,000 btu/h--------800 lbs.
      from cooldown----------------------------860
      transfer from condenser-----------------1,599
                Total-----------------------------3259 lb/h.

The adjustments mentioned above will reduce this figure a little, say to 3000 lb/h.

```
-------------------------------------------HEAT TRANSFER
  calculates unit and total conductivities of condenser  for
chip dryer
RATIO OF FREE AREA/TOTAL AREA = .4
NET AREA OF SECONDARY AIR CROSS SECTION = 13 SQ.FT.
VELOCITY = 19   VELOCITY FT./SEC.
h(fins) = 5.02 btu/h/°F/sq.ft.
 2305.69 sq.ft. surface area of fins
conductivity of fins = 11577.45 btu/h/°F total for fins
TUBE AREA = 1.000734 sq.ft. face area. total
G = 5500 mass flow of air and vapour, lb/h.
d = .09375 internal diameter in feet
h(air) = 5.67804 conductivity of air in tubes
h(water) = 717.651
h(tubes) = 63.83456 btu/h°F/sq.ft.
 341.5837 sq.ft. surface area of tubes in 8 ft. of condenser
 21804.85 btu/h/°F total for tubes in 8 ft. of condenser

OVERALL CONDUCTIVITY

overall  conductivity in 8 ft.  = 7562.226 btu/h/°F  through
                                   8ft. length of condenser
overall conductivity in 32 ft. = 30248.9 btu/h/°F
```

D.6 Illustration cont.

```
O LPRINT"-----------------------------------HEAT TRANSFER
LPRINT"  calculates  unit  and  total  conductivities  of
condenser for chip dryer"

REM CONSTANTS
m0=250:ml=3000'  lb/h mass flow of vapour and air in tubes
t=180'  temperature in tubes. °F
no=145'  number of tubes

FINS:
od=2.25:id=1.125:GRID=(2.875+2.5)/2
nf=6'  fins per inch
fr=.3'  ratio of fins to space between fins
L=8:W=4'  LENGTH AND WIDTH OF FACE
FLOW=15000'  FLOW IN CFM
AR=(1-fr)*(GRID-id)/GRID:LPRINT"RATIO  OF  FREE  AREA/TOTAL
AREA=":INT(100*AR)/100
NETA=L*W*AR:LPRINT "NET AREA OF SECONDARY AIR CROSS SECTION=":
  INT(10*NETA)/10;"SQ.FT."
VEL=FLOW/NETA/60:LPRINT "VELOCITY="INT(VEL);"VELOCITY FT./SEC.
hf=.99+.21*VEL' CONDUCTIVITY, BY ASHRAE (20),BTU/HR/°F/SQ.FT.
LPRINT "h(fins)=";INT(hf*100)/100;"btu/h/°F/sq.ft."
asf=no*L*3.141*(od/2) 2-(id/2) 2)*2*nf*L/144:LPRINT asf;
    "sq.ft.surface area of fins"
cf=hf*asf:LPRINT "conductivity of fins =";cf;"btu/h/°F total
for fins"

INSIDE:'  OF TUBES
TA=no*3.141*(id/2) 2/144:LPRINT"TUBE AREA=";TA "sq.ft. face
       area, total"
G=m)+ml:LPRINT"G=";G;"mass flow of air and vapour, lb/h"
d=id/12:LPRINT "d=";d;" internal diameter in feet"
ha=.0036*G .8/d .2' ASHRAE equation
LPRINT"h(air)=";ha;"conductivity of air in tubes"
hw=150*(1+.011*t)/d .2'  equation (14)
LPRINT "h(water)=";hw
ht=SQR(ha*hw):LPRINT"h(tubes)=";ht;"btu/h/°F/sq.ft."

ast=no*id*3.141*L/12:LPRINT ast;"sq.ft. surface area of tubes
in 8 ft of condser
cit=ht*ast:LPRINT  cit;"btu/h/°F  total for tubes  in  ft.of
condenser

LPRINT;LPRINT"OVERALL CONDUCTIVITY
ct=cf*cit/(cf+cit):LPRINT"overall conductivity in 8 ft.=
     ";ct;"btu/h/°F through 8 ft. length of condenser
LPRINT"overall conductivity in 32 ft. =";4*ct;"btu/h/°F.
```

D.4 Computer Simulation Test Results

Variations in Condenser Primary Flow

The air mass in the condenser primary is the same air which moved up from the highest point in secondary #1, with added heat from the furnace. To obtain high condensing temperatures this air needs a high enthalpy, which also means having a low mass flow-rate.

In this series of tests, the flows moving up from zone to zone is varied, leaving the preheat flows and the total flows constant. The recirculation flow is increased when output flow decreases.

Controlled Variation Primary Flow Dry Air Basis lb/h	Resulting Evaporation of moisture from chips	Coefficient of Performance based on 800,000 btu/h furnace ht.
4000	2611	3.26
6000	2676	3.34
8000	2686	3.36

Conclusion:

The best primary flow rate is slightly below the rate which produces maximum evaporation: the lower rate results in higher temperatures all through the dryer, and hence faster drying and increased product from the dryer.

D.4 Computer Simulation Test Results cont.

Variation of Furnace Heat

Starting with a capacity of one million btu/h, the program was run with furnace heat reduced in successive tests, with other conditions remaining constant.

Furnace Heat btu/h	Evaporation lb/h	Coef. of Performance	Final Moisture Content
1,000,000	3050	3.05	26.3
800,000	2854	3.57	27.8
700,000	2770	3.94	28.6%
600,000	2664	4.44	29.3%
500,000	2564	5.13	30.1%
400,000	2469	6.17	30.8%
300,000	2372	7.91	31.4%

Conclusion:

Although spectacular coefficients of performance are possible at low heat rates, this involves relatively high capital costs and labour costs. Minimum total costs result when there is a moderately high throughput of energy and chips.

D.4 Computer Simulation Test Results cont.

Variations in Mass of Chips

(initial moisture 45% wet basis)

Mass of Wet Chips lb/h	Water Removed	Coef. of Performance	Final Moisture Content
12,000	2686	3.36	29.1%
20,000	3461	4.33	33.5%

Conclusion:

The dryer can be pushed to high load rates without hurting its performance.

D.4 Computer Simulation Test Results cont.

Variations in Initial Moisture

Initial Moisture of Chips % wet basis	Evaporation	Coef. of Performance	Final Moisture %
45	2686	3.36	29.1
35	2619	3.27	16.9

Conclusions:

1. The dryer is almost as efficient at low moistures as at high moistures.
2. Operating conditions can be varied to produce an end product with any chosen moisture content, such as 25%.

D.4 Computer Simulation Test Results cont.

Variations in Ambient Temperature

Starting with a temperature of 80°F, runs of the program were made with the temperature reduced in successive runs.

Ambient Temperature deg F	Mass of Water Evaporated	Coef. of Performance
80	2428	3.03
50	2686	3.36
40	2758	3.45

Conclusion:

High ambient temperatures cause a reduction in the temperature difference available for heat recoveries available from the condenser and from cooldown.

The dryer works best in cold weather.

D.4 Computer Simulation Test Results cont.

Variations in Condenser Capacities

The condenser section in zone sec #1 caused instability due to its very small temperature difference where the secondary air is in contact with chips that are as hot as the primary air. Consequently this section of the condenser is reduced to a capacity of zero in all of the program runs. Zone 1 accomplishes most of the chip cooling.

It was intended to try incremental variations in the size of all of the condensers. However, when the system was showing the effects of having a condenser in zones 2, 3 and 4, the available temperature differences for heat transfer were 29, 29, and 51°F.

	Zones		
	Sec #2	Sec #3	Sec #4
Entering primary t	200	158	151
Lvg primary t	155	151	132
Entering sec t	118	113	68
Lvg sec t	138	133	102
Mean temp diff.	29	29	51

Since the heat transfer from any given section of condenser is proportional to its temperature difference a decision was made to work directly towards a larger temperature difference instead of making incremental changes in the capacities of the sections of the condenser.

These changes involved the following:

- concentrating all of the heat exchanger capacity in zone #3
- using zones sec #1 and #2 to cool the chips and to obtain some concentration of energy in the two top leaving streams, i.e. the air entering the primary drying zone and that entering the top level preheating
- the cooling of the chips before entering zone sec #3 helps to keep the average secondary temp. in the zone as low as possible, making for a high temperature difference

D.4 Computer Simulation Test Results cont.

- by having no condensing in zones sec #1 and #2, we get a top primary temp. of 200°F to 212°F in sec #3 instead of the dewpoint temperature of as low as 155°F
- the elimination of a condenser from zone sec #4 has the double effect of reducing the secondary temperatures in sec #3 and reducing the heat loss from warm product leaving the dryer.

The concentrating of the secondary heating all in sec #3 worked as follows:

run M14-10	10,000 BTU/h/° in each of 3 zones	evaporation 2680 lb/h
run M17-1	10,000 BTU/h/° in 1 zone alone	2642 lb/h

Thus the size of the condenser has been reduced by a factor of three with negligible effect on the performance of the dryer.

D.4 Computer Simulation Test Results cont.

Variations in Fan Flows

Fan flow rates in the program are stated in terms of mass flows (lb/h) although the fans are rated by volumetric flow rates (cfm). Depending upon the temperature, a typical fan with a rating of 15,000 cfm would deliver about 60,000 lb/h.

In this series of test runs the mass flow rates in secondary #1 was varied.

Flow rates	#2 60,000	#3 60,000	#4 60,000
Condenser capy.	10,000	10,000	10,000

Test #	Mass Flow Sec #1	Evaporation lb/h
M12-10	24,000	2941
M12-11	22,000	2937
M12-12	20,000	2937
M12-13	18,000	2934
M12-14	16,000	2923
M12-15	14,000	2923
M12-16	12,000	2921
M12-17	10,000	2920

Conclusions:

1. Results are changed very little by variations in the flow rate in zone sec #1.
2. Further optimization will involve reductions in the flow rate after the more crucial numbers have been optimized.

D.5 Calculations of Dryer Performance

General

The performance of individual small sections of the dryer is calculated by many iterations using the equations shown below. In each case, some of the variables which are used in an equation are ones which are determined by subsequent equations. The process is started by using estimated values for all variables, which are replaced by calculated values in subsequent iterations, repeated until the numbers stabilize within a 5% accuracy.

These calculations are in British units, using psychrometric tables from the ASHRAE Guide.

Examples, based on transfers in sec #4 condenser.

Temperature Difference between primary & secondary of condenser

temp of primary air entering this zone = tpc4

temp of primary air leaving this zone = tpc5

temp of secondary air entering this zone = te4

average temp of secondary air leaving condenser = tcd4

temp difference across condenser

$$td4 = (tpc4 - tcd4) \times (tpc5 - te4)^{0.5} \quad , \text{°F}$$

Heat conducted from condenser

conductivity C = 8000 btu/h for each °F of temp diff

$$hcd4 = C \times td4 \qquad \text{btu/h}$$

D.5 Calculations of Dryer Performance cont.

At the end of the calculations the program calls the printer subroutine to provide hard copy of some of the results.

Calculations

The following examples and explanations are based on the coding in the CALC4 subroutine, which applies to zone sec #4 and is typical of all secondary zones.

Temperature Difference at Condenser

```
td4 = SQR((tcp4 - tcd4) * (tcp5 - tc4))
```

or td = SQR ROOT OF ((PRIMARY ENT. TEMP - SEC LVG. TEMP)

X (PRIMARY LVG.TEMP - SEC.ENT.TEMP))

Heat Transfer from Condenser

```
hcd4 = C * td4
```

or heat transferred to secondary air = conductivity of condenser times temperature difference.

Enthalpy of Condenser Primary

The primary of the condenser cools rapidly to its dewpoint and then cools slowly while condensing occurs.

```
ecp4 = hcp4/mp
```

or enthalpy of primary air in condenser as it enters zone 4 = total heat in this air divided by its mass.

Temperature of Primary Air in Condenser

```
e = ecp4; GOSUB temp ; tcp4 = t
```

D.5 Calculations of Dryer Performance cont.

Temperature of Condenser Primary

temp of primary condenser entering zone (given) = tpc4

from psychrometric table for saturated air, enthalpy = ecp4

dry air mass in primary flow = mp
(set by the design of dryer)

enthalpy of primary leaving this section

ecp5 = ecp4 - hcd4/mp

for ecp5, a corresponding temperature tpc5 is found on the psychrometric table.

Heat leaving condenser

hlcd4 = he4 + hcd4

elcd4 = h/cd4/ms4

where he4 = heat entering condenser

ms4 = mass flow of air at fan #4

Temperature leaving condenser

tcd4 = te4 + hcd4/ms4/sha

sha is the specific heat of air.

In these calculations a value of 0.24 btu/lb/°F is used throughout.

Mass flow of fan

The volumetric flow, vf is taken as 15,000 cfm.

The temperature of air entering the fan is te4.

From a psychrometric table, the specific volume v at te4 is read,

ms4 (lb/h) = vf (cf/m) x 60 (m/h)/v (cf/lb).

PART

2

Energy, Mines and Resources Canada

Énergie, Mines et Ressources Canada

Hon. Marcel Masse, Minister

L'Hon. Marcel Masse, Ministre

Canada

DESIGN OF A TREE CHIP DRYING SYSTEM
PART II OF II

RENEWABLE ENERGY BRANCH

PREPARED FOR:

Renewable Energy Branch
Energy, Mines and Resources Canada
Ottawa, Ontario

DSS Contract File No: 51SZ.23216-6-6177

September 1987

PREPARED BY:

Intertech Engineering Corporation
199 Bay Street, Suite 503
Toronto, Ontario, Canada M5J 1L4
Telephone (416) 366-2135

SCIENTIFIC AUTHORITY

Dr. W.E. Lowe
Manager, Alternate Energy Development Program
Renewable Energy Branch
Energy, Mines and Resources Canada

1.1 TITLE

DESIGN OF A TREE CHIP DRYING SYSTEM
PART II OF II

RENEWABLE ENERGY BRANCH

PREPARED FOR:

Renewable Energy Branch
Energy, Mines and Resources Canada
Ottawa, Ontario

DSS Contract File No: 51SZ.23216-6-6177

September 1987

PREPARED BY:

Intertech Engineering Corporation
199 Bay Street, Suite 503
Toronto, Ontario, Canada M5J 1L4
Telephone (416) 366-2135

SCIENTIFIC AUTHORITY

Dr. W.E. Lowe
Manager, Alternate Energy Development Program
Renewable Energy Branch
Energy, Mines and Resources Canada

1.2 CITATION

CRINGAN, J.C., ISLES, R., BURRELL, C.
Intertech Engineering Corporation
Design of a Tree Chip Drying System

Report of Contract File No: 51SZ.23216-6-6177
Renewable Energy Branch; Energy, Mines and Resources Canada
Ottawa, Ontario 1987 (54 pp)

Copies of this report may be obtained through:

Renewable Energy Branch
Energy, Mines and Resources Canada
580 Booth Street
Ottawa, Ontario
K1A 0E4
(613) 995-9447

or

Interlibrary Loans
CISTI Library
National Research Council
Bldg. M-55, Montreal Road
Ottawa, Ontario, K1A 0S2
(613) 993-1585

C Ministre des Approvisionnements et Services Canada 1988

N^{o} de catalogue M91 - 7/18 - 1988 - 2E
ISBN 0-662-16389-3

1.3 ACKNOWLEDGEMENTS

ACKNOWLEDGEMENTS

Intertech Engineering Corporation wish to acknowledge the valuable assistance given by the following individuals, organizations, subcontractors, who were associated with the work of this project.

Dr. W.E. Lowe, Manager, Alternate Energy Development Programme, in the Renewable Energy Department of Energy, Mines, and Resources, Canada.

Dr. H.A. Becker, Professor and Head of the Chemical Engineering Department, Queen's University.

M. Leboldus, Graduate Student M.Sc. Programme, Department of Chemical Engineering, Queen's University.

DISCLAIMERS

This Report is distributed for information purposes only, and does not necessarily reflect the views of the Government of Canada, nor constitute an endorsement of any commercial product or person. Neither Canada, nor its Ministers, Officers, Employees or Agents, makes any warranty in respect of this Report or asssumes any liability arising out of the Report.

1.4 PREFACE

This report describes the technical and economic details of a design process to achieve an energy efficient wood chip dryer. The work was carried out under the Bioenergy Development Programme of the Renewable Energy Division of Energy Mines and Resources, Canada. The nature of the work centred on the design of heat recovery techniques to minimize the energy consumption of a wood chip dryer and then the optimization of the system under varying conditions of operation in order to determine and compare the real cost of drying wood chips on a unit energy delivered basis.

The intended purpose of the work can be described as follows:-

- Develop new equipment processes, and techniques for economic moisture content reduction of wood chips, whereby the increase in calorific value of the chips due to moisture removal, would significantly outweigh the real cost of processing.
- Prove by detailed cost estimates based on the design of the proposed drying system, the real cost of drying wood chips on a net unit energy delivered basis at varying conditions of product and system operation.

The scope of the work was limited to:-

- processing of tree chips as normally sized for household heating applications
- rating of the system to be 4000 tonnes per year dried basis
- investigation of existing chip drying systems
- design of a preferred system to produce economic drying of chips
- analysis of energy, mass flow, and computation of total costs of a preferred drying system including drying, transportation, storage, and combustion
- recommendations for application of the proposed system to other biomass materials.

1.4 Preface cont.

The significant features of the work completed in this project were found to be that

- multiple recovery of heat in a drying system can reduce the energy consumption by a factor of four compared to single pass drying systems
- total energy required to remove one pound of water from wet chips with moisture contents ranging from 50 percent to 25 percent was in the range of 350 BTU
- multiple recovery of heat as a technique in drying systems can be applied to all sorts of commodities for major economies in energy
- net annual savings for residential heating with dried wood chips ranges from $300 to $1000 for small to large homes respectively compared to oil heating.

This report has been prepared with the objective of

- formalizing the work carried out under contract to Energy Mines and Resources
- demonstrating the economic merits of drying tree chips with a regenerative or multi recovery of heat drying system
- providing some cost and construction details of a 4000 tonne per year chip dryer
- acquainting those in both the public and private sectors especially those in the tree chip business with a "state-of-the-art" drying system.

Those using the technical information from this report should be aware of the fact that some but not all of the technology is the proprietory information of Intertech Engineering Corporation since one of their major lines of business is drying technology.

1.5 ABSTRACT

Intertech Engineering Corporation have carried out a study on the Design of a Tree Chip Drying System in accordance with Contract Number 23216-6-6177/01-SZ issued by the Department of Energy, Mines and Resources as part of their Bioenergy Development Programme.

The objectives of the work were:-

- Design and selection of a drying system for wood chips to obtain the lowest cost per tonne of dried product.
- Determination of the drying characteristics of a wood chip dryer in terms of energy required to remove a pound of water at various operating conditions of the dryer, product, and atmosphere.
- Determination of the real cost of drying wood chips on a cost net unit energy delivered basis as compared to costs of wet chips.
- Verification of chip drying characteristics by bench tests.
- Estimation of costs involved in transportation, storage etc.
- Calculation of fuel burning efficiencies and heating costs.

The work was carried out by review of existing methods for drying tree chips ie. evaluation of the state of the art, followed by preliminary designs of the dryer in the form of drawings. Mass and energy flow balances were calculated and one of the preliminary designs selected for detail study and evaluation. Detail drawings on the selected design were prepared along with capital and operating cost estimates. Finally a computer programme was designed to carry out the optimization of the performance of the dryer at various conditions of operation.

The results show that a medium temperature, atmospheric dryer, of the regeneration type with multi stage recovery via a tube in shell heat exchanger and a nominal rating of 2000 pounds per hour of water removal from wood chips can be built and operated with a coefficient of performance (COP) ratio of between 4 and 5. This means that for every heat energy unit used in the process, there will be a four to five fold increase in the heating value of the wood chips within the range of drying from 50 percent moisture to 25 percent moisture. With regenerative drying of wood chips the fuel cost of residential heating can be reduced from one half to two thirds compared to heating with oil depending on the size of residence.

5

1.5 Abstract cont.

The results of this project are significant in that it has been demonstrated that the technique of multiple recovery of heat in a drying system can reduce energy consumption by a factor of four compared to single pass drying systems. In addition this technique if applied correctly could be utilized in the drying of all sorts of biomass materials, and as a result would result in major economies in energy consumption.

In the specific case of wood chips in which this project was directed, it was demonstrated that the total energy required to remove one pound of water from wet chips with moisture contents ranging from 50 percent to 25 percent is in the range of 350 BTU.

1.6 TABLE OF CONTENTS

1. FRONT SECTION

1.1 TITLE..(i)

1.2 CITATION.....................................(ii)

1.3 ACKNOWLEDGEMENTS.............................(iii)

1.4 PREFACE......................................(iv)

1.5 ABSTRACT.....................................(vi)

1.6 TABLE OF CONTENTS............................(viii)
  1.6.1 List of Figures..........................(x)
  1.6.2 List of Tables...........................(xi)

1.7 EXECUTIVE SUMMARY............................(xii)

1.8 RESUME.......................................(xiv)

2. CORE SECTION

2.1 INTRODUCTION................................. 1

2.2 OBJECTIVES................................... 2

2.3 METHOD....................................... 3

2.4 DATA USED IN THE ESTIMATES................... 4

2.5 COST OF WET TREE CHIPS AT THE DRYER SITE..... 5

2.6 COST OF TRANSPORTING TREE CHIPS.............. 6

2.7 COST OF DRYING THE TREE CHIPS................ 7
  2.7.1 General.................................. 7
  2.7.2 Capital Estimate......................... 7
  2.7.3 Operating Costs.......................... 7
  2.7.4 Costs of Drying Tree Chips at Various Feed Rates and Moisture Content of Product.......... 8
  2.7.5 Costs of Drying Tree Chips by Alternative Drying Systems..................................11

2.8 STORAGE COSTS................................12

2.9 TOTAL COSTS OF TREE CHIPS INCLUDING DRYING...13

TABLE OF CONTENTS cont.

2.10 EFFICIENCY OF BURNING....................................14
2.10.1 Evaporating Water....................................14
2.10.2 Excess Air....................................14
2.10.3 Boiler Efficiency....................................15
2.10.4 Heat Output....................................15
2.10.5 Steam Generating Capacity....................................15

2.11 HEAT ENERGY FROM BURNING TREE CHIPS WITH VARIOUS MOISTURE CONTENTS....................................17

2.12 OBSERVATIONS AND DISCUSSIONS....................................18

2.13 FIGURES & TABLES....................................19

3. FINAL SECTION

3.1 CONCLUSIONS....................................47

3.2 RECOMMENDATIONS....................................48

3.3 REFERENCES....................................49

3.4 APPENDICES....................................51

Appendix A - Contract Directory Information....................................52
Appendix B - Disclosures Certification....................................54

1.6.1 LIST OF FIGURES

1. Effect of Size of Dryer on Relative Capital Cost for Evaporation
2. Effect of Size on Operating Costs per Tonne
3. Mass and Energy Flow Diagram
4. EMR-IEC Tree Chip Drying System
5. Process/Energy Flow Diagram
6. Tree Chip Transport Costs
7. Wood Chip Moisture Content Effect on Boiler Efficiency
8. Wood Chip Moisture Content Effect on Boiler Output
9. Relationship of Wood Chip Moisture to Effect of Steam/ Boiler Output
10. Effect of % Moisture on Heating Costs of Tree Chips

1.6.2 LIST OF TABLES

1. Specific Weight/Specific Volume for Wood

2. Properties of Wood

3. Calorific Value of Chips at Various Moisture Contents, Wet Wt. Basis

4. Estimated Costs of Green Chips

5. Estimated Costs of Chips (20% MC)

6. Tree Chip Dryer - Mass Flow Rates for Air & Water at a Nominal Operating Condition

7. Energy Flow Legend - Attach to Drwg.

8. Energy Flow Rates at a Nominal Operating Condition

9. Capital Estimate - IEC Dryer

10. Operation Estimate - IEC Dryer

11. Total Costs of Dried Chips (From Thin Operations)

12. Total Costs of Dried Chips (From All Types of Operations)

13. Heat Loss Associated with Water Vapour in Flue Gas as Percentage of Higher Heating Value of Dry Fuel

14. Costs per Million BTU of Output - Wood from Thin Operations

15. Costs per Million BTU of Output - Wood from All Operations

1.7 EXECUTIVE SUMMARY

The project evaluated the technical and economic feasibility of drying wood chips. The work combined cost data obtained by the design of a high-efficiency dryer with literature information to estimate the cost of heating.

Cost elements considered were:

- cutting and gathering
- chipping and delivered to the dryer
- drying
- storage
- delivery to customer
- furnace efficiency.

Cutting and gathering of wood can represent almost 60% of the cost of delivered costs of wood chips. Therefore, for near-future markets it is necessary that wood be supplied from thin operations - where cutting and gathering is charged to the woodlot. In the long term, it is desirable to develop more efficient ways of cutting and gathering.

Where the wood is free (from a woodlot thin operation or from a sawmills residue) green chips delivered to the dryer represent slightly more than half of the total costs of chips delivered to a furnace site. For undried chips storage and delivery charges each represent about one-quarter of that cost. Drying by the method developed in this project represents no more than 11% of the costs of wood chips delivered.

Chips delivered to furnace cost $51.30/tonne undried to $70.28/tonne after drying. Because only the solids portion of the chip produce heat, the cost per million BTU drops from $6.54 to $3.98 as the moisture content is chopped.

Furnace efficiency also plays a major role in determining heating costs. Moisture must be driven out - either in a dryer or in the furnace. When wet fuel is used the furnace must be supplied with additional excess air to ensure sufficient oxygen is available. Typically furnaces produce less than 60% of the theoretical heat from 60 moisture content (M.C.) fuels. This efficiency raised to over 75% for fuels with less than 20% M.C.

High moisture (say over 60% M.C.) fuels cause furnaces to black out.

To prevent handling problems - freezing and fungal - the moisture content should be below 24% but not so low as to encourage the moisture to recombine.

1.7 Executive Summary cont.

Considering the costs of delivered and the efficiency of burning, the heating value of wood chips drying reduces the costs from \$11.24 to \$5.10/per million BTU - cutting out over half the costs. At these costs dry wood chips are more than competitive with oil and electricity for space heating in the Maritimes, and similar regions of Canada.

It is recommended that a demonstration dryer facility should be set up.

Le séchoir Intertech comporte une petite section de séchage à haute température qui donne de l'air quasi-saturé dont la température avoisine le point d'ébullition de l'eau. Ainsi, la chaleur secondaire tirée du condenseur atteint une température variant entre une valeur légèrement inférieure au point d'ébullition de l'eau et une valeur légèrement supérieure à la température ambiante. La durée du séjour des copeaux dans le séchoir est déterminée de façon à les faire sécher correctement en fonction de la température.

Par exemple, à la température type de 70° C de l'air de condensation, quand 1 kg d'air saturé est refroidi de 1°, le transfert d'énergie est suffisant pour ajouter 1° de surchauffe à 46 kg d'air.

La circulation d'une masse d'air plus importante dans la section secondaire du condenseur est obtenue grâce à quatre ventilateurs qui fournissent un débit total plusieurs fois plus important que celui de la section primaire.

Récupération multiple de la même énergie

Si on ne devait récupérer que la chaleur primaire dans le condenseur, le maximum de chaleur secondaire qu'on obtiendrait serait limité à l'énergie primaire, moins les pertes par conduction, moins la partie irrécupérable (à un coût économique) en raison de sa température trop basse.

Avec notre système à récupération multiple, la Section de séchage secondaire fournit aussi de la chaleur latente que l'on peut récupérer. Cette chaleur latente est produite par la chaleur secondaire et par le refroidissement des copeaux. À chaque étape du chauffage secondaire, une partie de la chaleur latente sert à pré-chauffer les copeaux et une autre partie monte dans les quatre divisions de la zone secondaire pour servir d'air de combustion pré-chauffé.

Supposons que la perte d'énergie dans un séchoir soit de l'ordre de 25 p. cent à chaque cycle de chauffage-séchage.

Un séchoir non régénérateur aurait une efficacité maximum E de

$$1 - 0{,}25 = 0{,}75 = E \qquad (1)$$

Avec une seule étape de récupération de la chaleur, l'efficacité devient

$$E + E^2 = 1{,}31 \qquad (2)$$

INTERTECH ENGINEERING CORPORATION

RÉSUMÉ À L'INTENTION DE LA DIRECTION

CONCEPTION D'UN SÉCHOIR DE COPEAUX

Ce rapport décrit un séchoir régénérateur conçu par Intertech Engineering Corporation qui a reçu l'aide d'Énergie, Mines et Ressources. Le séchoir utilise des techniques de récupération d'énergie qui réduisent la consommation d'énergie au quart de celle d'un système à passage unique.

Quand on fait sécher quelque chose, l'énergie qui semble disparaître en évaporation est toujours là sous forme de chaleur latente. On a mis au point des techniques permettant de récupérer une partie de l'entropie grâce à une section de préchauffage et à la récupération de l'énergie par le générateur d'air chaud et un condenseur.

Sommaire

Le séchoir régénérateur Intertech fonctionne de la façon suivante : un lit de copeaux (d'une épaisseur de 10 à 30 cm) en mouvement traverse des zones dont la température va en augmentant, jusqu'à ce qu'il atteigne la section de séchage primaire. Il subit ensuite un séchage secondaire dans des zones dont la température va en décroissant pour atteindre une température avoisinant celle de la pièce. L'air qui circule en sens inverse en tourbillonnant est aussi chauffé, puis refroidi avant d'être évacué de l'extrémité froide de la section de préchauffage.

Récupération de l'énergie

Le transfert d'énergie qui s'effectue dans un séchoir illustre bien les effets de la loi de la conservation de l'énergie et de la loi de l'entropie : peu importe l'utilisation de l'énergie, elle existe toujours, mais chaque transformation la rend plus difficile à utiliser par la suite.

Nous allons voir comment ces lois s'appliquent au fonctionnement d'un séchoir régénérateur et comment les caractéristiques du modèle Intertech lui permettent de réduire les pertes au minimum et de réutiliser plusieurs fois l'énergie.

Perte de chaleur

Chaque fois qu'une partie de l'enthalpie de la vapeur est convertie en chaleur sensible par condensation, on a comme résultat :

- une chute de la température
- un écoulement d'air considérablement accru, pour acheminer l'énergie sous forme de surchauffe plutôt que de vapeur.

RÉSUMÉ À L'INTENTION DE LA DIRECTION (suite)

Quand on utilise la même énergie plusieurs fois, on a un coefficient d'efficacité de

$$E + E^2 + E^3 = + E^n = 3 \qquad (3)$$

On pourrait aussi réduire les pertes d'énergie à moins de 25 p. cent si on avait un séchoir plus gros, plus lent et mieux isolé. Toutefois, cette valeur est typique des systèmes modernes et une plus grande réduction des coûts impliquerait des investissements excessifs.

PRÉ-CHAUFFAGE ET REFROIDISSEMENT

Pré-chauffage

Quand un objet non réchauffé est séché à l'air chaud

- une grande partie de l'énergie ne sert qu'à chauffer l'objet
- le refroidissement par évaporation ralentit le processus de chauffage
- la déperdition d'eau de l'objet est ralentie par sa basse température.

Dans le cas du séchoir Intertech, une partie de l'air humide de recirculation provenant du séchage sert à chauffer les copeaux verts sans évaporation. Ainsi, on obtient un séchage primaire rapide pendant lequel l'humidité se transfère à la surface, pour le séchage secondaire.

Refroidissement

Dans le séchoir Intertech les copeaux sont refroidis graduellement par évaporation dans la zone de séchage secondaire. Cette action s'ajoute à l'effet d'évaporation causé par la chaleur secondaire.

Renouvellement de l'air dans la zone secondaire

Si l'accumulation de chaleur dans la zone secondaire s'effectuait sans contrôle, l'humidité augmenterait, et empêcherait le séchage. Afin d'empêcher un taux excessif d'humidité, la zone de séchage secondaire comporte quatre divisions dans lesquelles l'air de reprise atteint des taux d'humidité différents et les températures du point de condensation décroissent avec celle des copeaux.

L'air le plus chaud et le plus humide d'une division monte dans la suivante. La division supérieure contient l'air qui renferme le plus d'énergie. Cette partie alimente le générateur d'air chaud en air de combustion pour le séchage primaire.

RÉSUMÉ À L'INTENTION DE LA DIRECTION (suite)

Une partie de l'air de reprise de chacune des divisions passe à la zone de pré-chauffage et est remplacée par de l'air de recirculation du séchage secondaire. Par conséquent, l'air qui sort des copeaux partiellement séchés a un taux d'humidité relative élevé, mais la surchauffe ajoutée au condenseur réduit le taux à moins de 25 % pour assurer un séchage efficace.

CHAUFFAGE RÉSIDENTIEL - ÉCONOMIES

Le chauffage automatique aux copeaux secs peut réduire la facture de combustible pour une maison de la moitié aux deux tiers, selon le prix des copeaux de bois.

À Toronto, le mazout coûte 29,9 cents le litre. Pour un chauffage ayant un taux d'efficacité de 80 %, le million de kJ revient à 9,48 $.

En comparaison, les copeaux séchés au coût de 50 $ la tonne donnent 8 750 BTU par livre avec une efficacité d'environ 75 %, ce qui signifie une économie de 3,27 $ par million de kJ, voire davantage selon les prix.

Toutefois, une partie de ces économies est perdue à cause du coût de financement plus élevé du brûleur automatique de copeaux et du local à l'épreuve du feu où l'on entrepose les copeaux.

	Grosse maison	Maison moyenne	Petite maison
Consommation annuelle de mazout	2500	1500	1000
Amortissement annuel de l'installation	275	200	150
Coût total	2775	1700	1150
Consommation annuelle de copeaux	862	517	345
Amortissement annuel de l'installation (y compris la salle d'entreposage)	900	665	500
Coût total	1762	1182	845
ÉCONOMIE NETTE	1013	518	305
ÉCONOMIE EN POURCENTAGE	36%	30%	26%

RÉSUMÉ À L'INTENTION DE LA DIRECTION (suite)

La combustion des copeaux de bois

Nos calculs ont révélé que la production de copeaux de bois secs comporte de grandes variations de prix de chaque composant. Évidemment, ces variations ont une influence déterminante sur la rentabilité d'une entreprise.

On peut dire que le prix des combustibles fossiles finira par atteindre un seuil si élevé que le marché des copeaux sera viable partout où il y a des possibilités d'approvisionnement et des bâtiments à chauffer en quantité suffisante. (Ce qui est déjà le cas dans les pays scandinaves.) Si on peut acheter de la chaleur résiduelle dont la température dépasse celle du point d'ébullition de l'eau, on abaisse les coûts de quelques dollars par tonne. On peut aussi économiser environ 10 $ par tonne si on procède à partir de copeaux qui proviennent de résidus industriels plutôt que d'arbres. Au cours des premières années, quand les générateurs d'air chaud seront importés et le marché des copeaux en expansion, les fournisseurs de copeaux les mieux placés seront vraisemblablement ceux qui pourront bénéficier de coûts réduits pour la matière première ou pour l'énergie.

Les coûts, peuvent varier énormément selon les quantités produites et vendues. Une entreprise devrait avoir un marché établi pour une grande partie de sa production (disons 50 %) si elle compte atteindre le seuil de rentabilité.

Le marché des copeaux de bois

D'après notre étude, avec un coût de 50 $ et même de 75 $ la tonne de copeaux séchés, on peut réaliser des économies par rapport au mazout pour à peu près n'importe quel type de maison. Toutefois, tant que le mazout est disponible à un prix accessible, l'économie nette doit être assez importante pour vaincre l'inertie humaine. Par exemple, à peu près personne ne serait intéressé par une économie de 100 $. Par contre, dans les régions rurales et les villes où le bois constitue déjà une partie des sources de chauffage, on serait très intéressé par une économie de 1 000 $.

Les économies réalisées, tant en valeur absolue qu'en pourcentage (par rapport au chauffage au mazout) sont proportionnelles à la taille de système de chauffage. Par conséquent, le chauffage aux copeaux pourrait être très intéressant pour les petits immeubles d'appartements, de centres commerciaux, de petites usines et très grosses maisons.

RÉSUMÉ À L'INTENTION DE LA DIRECTION (suite)

ANALYSE COÛTS/BÉNÉFICES POUR UN SÉCHOIR DE COPEAUX

Coûts énergétiques

Générateur d'air chaud	750 000 kJ/h à 3,00 $ par million de kJ	= 2,25 $/h
Électricité	150 000 kJ/h à 5 cents le kWh et 36MJ/kWh	= 2,08 $/h
Coût total		= 4,37 $/h

Main d'oeuvre

Fonctionnement (2 personnes à temps partiel (qui effectuent un autre travail la plupart du temps)	= 5,00 $/h
Entretien (10 000 $ par année)	= 2,00 $/h
Coût total du fonctionnement	= 11,37 $/h
Coût de fonctionnement à 5t/h	= 2,27 $/h

Coût en capital

Un séchoir d'une capacité de 5 t/h coûte environ 155 000 $. Ce prix comprend les panneaux isolants, l'ossature d'acier, les cloisons, un gros échangeur de chaleur, un convoyeur, les ventilateurs, un générateur d'air chaud, les câbles et commandes électriques, divers dispositifs et 25 000 $ pour les imprévus.

En outre, il faut compter le prix d'un bâtiment et de l'équipement de manutention des copeaux. On ne compte pas ici les coûts de l'équipement de production des copeaux qui sont calculés dans le prix des copeaux verts. L'installation, y compris le bâtiment, coûte environ 250 000 $. On peut financer une telle somme à raison de 34 000 $ (capital et intérêt) par année pendant 20 ans.

Si on calcule 5 000 heures de fonctionnement par année, on a un coût en capital de 6,80 $/h ou 1,36 $ par tonne de copeaux.

Le coût total (fonctionnement et capital) du séchage des copeaux s'établit donc à 3,63 $/t.

Avantages du séchage des copeaux

Le séchage des copeaux donne une augmentation notable de la chaleur nette produite par tonne de solides. En outre, il permet de transformer en combustible résidentiel une matière qui ne serait autrement utilisable que pour les installations industrielles.

Un tableau produit par R.L. Stewart a été cité dans plusieurs études. Il montre l'efficacité du bois qui varie entre 77 %, à 10 % d'humidité (à l'état humide), et 58 %, à 60 % d'humidité (à l'état humide). À partir de ce tableau et d'une valeur de départ de 8 750 BTU/lb par le bois de l'écorce (à l'état sec), chaque 1 % d'humidité (à l'état sec) donne 15 BTU de chaleur disponible par livre de copeaux. En termes plus clairs, pour chaque libre d'eau que l'on extrait des copeaux, on gagne 1 500 BTU. Ce chiffre correspond aux 1 000 BTU nécessaires pour faire évaporer l'eau dans le générateur d'air chaud plus 500 pour l'air supplémentaire et la combustion incomplète qui se produit quand la fournaise se rapproche de son point d'inefficacité. Un autre avantage du séchage des copeaux est le fait que l'on peut augmenter jusqu'à 50 % la chaleur produite par une fournaise en passant des copeaux humides aux copeaux secs.

Chaleur nette tirée des copeaux humides	0.6 x 8 750 = 5 250 BTU/lb
Chaleur nette tirée des copeaux secs	0.75 x 8 750 = 6 562 BTU/lb
Gain tiré du séchage	1 312 BTU/lb x 2 204 = 2,89 MBTU/t

Notre évaluation du coût de séchage des copeaux à 2,27 $/t compte 2 700 lb d'eau pour 5 tonnes de copeaux, ou 540 lb d'eau par tonne, ou 0,245 lb d'eau par livre de copeaux. Sans séchage naturel préalable, le coût pourrait grimper à 5,00 $ par tonne, ou 5,00 $/2,99 MBTU, soit un coût de 1,73 $ par MBTU de chaleur économisée par le séchage. Ce coût est bien inférieur à celui des autres sources énergétiques.

On a mis au point un logiciel qui calcule la masse, les écoulements, la température et les enthalpies à quatre-vingt-dix endroits différents du système de séchage.

Ainsi, on pourra tirer un rendement optimal du séchoir selon les variations de température et le taux initial d'humidité des copeaux.

INTERTECH ENGINEERING CORPORATION

DESIGN OF A TREE CHIP DRYING SYSTEM
PART II OF II

FINAL REPORT

2. CORE SECTION

2.1 INTRODUCTION

Canada has large supplies of all types of fuels and energies: coal, hydro, natural gas, oil, peat, and wood. The questions are convenience, cost, local availability, long-term supply, and security of supply.

Historically, much of Canada's heating was supplied by wood, then by coal, and more recently by more convenient natural gas and oil. But costs of natural gas and oil are rising rapidly. Natural gas is not available in parts of the country. Oil has had recent supply crises and dramatic price fluctuations. Because of these crises and fluctuations there has been a search for alternate energies.

This search has been led by Energy, Mines and Resources Canada, and by its provincial counterparts. Of particular interest to the Maritimes region has been the use of wood. But roundwood was superceded by oil in these regions because of the greater convenience of oil.

Wood chips offer the potential to use wood with convenience of automatic fueling by use of a stoker. Further, wood chips mean that secondary woods - smaller branches - would be chipped and used rather than discarded.

This report looks at the various steps in the process of taking wood and converting it into useable chips, including transporting, storage, drying and burning efficiencies. The need for drying is demonstrated. An efficient dryer is proposed. Costs for the various process steps are determined. Finally, variation of heating costs with chips' moisture content is estimated.

2.2 OBJECTIVES

The general objective of this project was to evaluate the economic advantage of burning dried wood chips as opposed to burning wet chips. More specifically, the objectives are to report on the following:-

- estimates of overall costs of drying tree chips down to various levels of moisture content.
- the total estimated cost of dried tree chips with various moisture contents.
- the heating value of these dried chips based on typical furnace efficiencies.
- conclusions and recommendations based on these estimates.

The real question is this:-

- What is the most economic level of moisture that should be used in wood chips when burned as a fuel.

2.3 METHOD

This project had three elements:

- review of literature on wood chips and fuel burning,
- design of a high-efficiency dryer, and
- combining these data.

In-house literature was complemented with data from the CISTI Library, National Research Council Canada, the Solar Research Institute, and from data gathered by attendance at several conferences on wood chip fuels. These data were analysed to obtain cost estimates for each of the several activities in producing dry wood chips and to obtain data on the effect of moisture on furnace efficiencies.

Much of the work was designing a high-efficiency dryer for use as the central element in the overall process. A wide variety of drying approaches have been reported in the literature. Among the approaches considered have been heat from oil, natural gas, wood products, geothermal, greenhouse, and ambient air blown through the chips.

The high energy dryer, discussed in Section 2.7, uses multi-stage drying and condensing to salvage heat. The multi-stage drying approach provides the method to supply air at temperature/moisture combinations most appropriate to the conditions of the wood chips at that special stage of the wood chips' drying.

Finally, all the literature and design data are combined to show the effect of drying wood chips on the cost of heating.

2.4 DATA USED IN THE ESTIMATES

Tables 1, 2, and 3 provide basic data on wood chips. Table 1 gives specific weight/specific volume information for chips made from hardwood and softwood. It also shows the volume expansion ratios due to chipping.

Table 2 shows information in the specific gravity of fourteen different species - each at two different moisture levels.

Solid wood has a calorific value of 8,750 BTU per pound. The calorific value of fuel with various moisture/solids ratios were calculated for Table 3.

2.5 COST OF WET TREE CHIPS AT THE DRYER SITE

Tables 4 and 5a & b gives the estimated and test sites costs of chips at the site.

Table 4 gives estimated costs of clear cutting, strip clear cutting, mechanized thinning or trail cutting operations which can be performed effectively with (relatively) small equipment. The source report considered that sites had a stand density of at least 100 tonnes/ha and exceeded 10 ha in operable area. Calculations assumed that the average stand diameter was 15 cm. These seven calculations predicted values from 21.31 to 35.18, with an average of $25.53/tonne.

Costs shown in the reference for Table 5 range from $36.67/tonne to $198.21/tonne.

Table 5a summarizes results from nine tests done by the University of New Brunswick. This involved two blocks with slash, three block that were thinned, and five blocks that were cleared. Costs included delivery - for our purposes assumed to be to the dryer. Costs (adjusted to 20% MC dry basis) ranged from $38.67/tonne to $198.21/tonne with an average of $148.79/tonne.

That source (p 101) reports labour was 50% of the total cost. Operating costs (fuels, repairs, etc.) were 19%, another 19% went to fixed costs, and the remaining 12% was spent to transport the chips from roadside to a central storage area.

Table 5b presents data on the experimentally-derived costs of green chips as ranging from $66.30 to $165.43/tonne with an average of $106.56/tonne. These values considerably exceed the current market prices (cited by ENFOR Project P-302, page 42) of $25 to $27/green tonne for chips for fiber and $14 to $16/green tonne for chips for fuel.

The closest the UNB test work comes to these current market prices would be where the major objective was thinning, and all of the labour was charged to that activity. Alternately, sawmill scrap could be used. Then the delivered cost of $1,314.75 (ref.Table 7.11) divided by the 49.0 tonnes produced would be $26.83/tonne. Excluding delivery, cost would be $712.95/49.0 or $14.55 - a value comparable to the actual market prices.

At this stage in the development of the use of wood chips for fuel, sufficient chips can be obtained from woodlot thinnings where the cost of thinning is charged to the woodlot. Cost of the chips at the roadside will therefore be taken at $14.55/green tonne. This corresponds to $26.83/green tonne delivered to a central storage area.

2.6 COST OF TRANSPORTING TREE CHIPS

The UNB report (CREDA Project #2023, table 7.2 through 7.10) provides data for container service of $6.56 & $12.66/green tonne for 18 km and 58 km respectively.

These data are included on Figure 6. This figure also includes data from ENFOR Project P-302. These data indicate that the most important consideration is the quantity to be trucked per day - varying from about $15/tonne at 25 tonnes/day to about $5/tonne at 100 tonnes/day. Added to this is a mileage charge of about $3/tonne per 100 km.

2.7 COST OF DRYING THE TREE CHIPS

2.7.1 General

Data on the cost of drying tree chips was gained from two sources:

1. Detail design of high efficiency dryer.

2. Literature - primarily for pulp mill use.

2.7.2 Capital Estimate

Table 10 provides a capital cost estimate for the IEC dryer. This dryer is designed to provide very efficient use of energy (for heat and power). Significant features of this dryer are shown in figures 3, 4, and 5, which show the mass and energy flow, the system, and the process/ energy flow respectively.

Including a 20% contingency, the estimated capital cost is $155,239 - transport and foundations extra. Of the defined total - $129,366 - over 61% is spent for structural material (36%), conveyor material (12%), and assembly labour (12%).

This capital cost estimate is added to figure 1 - which shows data from the literature. Note that the IEC data appears low because administration, engineering, and marketing costs are not included in the IEC data.

2.7.3 Operating Costs

Calculations of operating costs is given as Table 11. Total operating cost is made up of heat energy, electrical energy, labour, and maintenance. These costs are estimated of $6.25/hr, $2.08/hr, $5.00/hr and $5.00/hr respectively. The total of $18.37/hr is equivalent to $4.12 per tonne of chips.

To this must be added a capital charge of $34,000/yr. ($155,000/amortized over 5 years).

Therefore total drying cost would be $7.93 tonne. This data is plotted on figure 2 - which shows literature data on the effect of size. Other production rates are shown in Section 2.7.4.

2.7.4 Costs of Drying Tree Chips at Various Feed Rates and Moisture Content of Product

2.7.4.1 Effect of Different Operating Rates

Assume that green chips are burnt. These cost $26.83/ green tonne at the dryer (from last para of 2.5). The moisture content of thinning ranged from 44 to 73% M.C. dry basis (from Table 5b) or 30.6 to 42.2% M.C. wet basis using an average of 36.4%. From Figure 8 we find that at that M.C., boiler output is 4,000 BTU/lb of wood chips. Since the boiler produces 10^6 BTU/hr, (from figure 5) the boiler needs 10^6/4,000 or 250 lb/hr. This is $3.04/hr for fuel.

Details of the cost are therefore:

$155,000 dryer + $95,000 related buildings etc. amortized over 20 years - $34.000/yr.

Heat Energy -	$ 3.04/hr
Electric Energy -	$ 2.08/hr
Labour -	$ 5.00/hr
Maintenance -	$ 5.00/hr
Total Hourly Costs	$15.12

If we vary both the annual use and the tonnes/hour (because of moisture considerations) we find-cost/tonne

Operating Hrs/yr.	Infinite	5,000	3,500	2,000
Capital Charges/hr	----	$6.80	9.71	17.00
5 tonne/hr	3.38	4.91	5.56	7.19
4 tonnes/hr	4.23	6.14	6.96	8.99
3 tonnes/hr	5.64	8.19	9.27	12.00

From the above, it is clear that a viable chip business requires that:

- the dryer be operated for a relatively high production rate
- there be sufficient sales of chips to keep the dryer busy for much of the year.

2.7.4.2 Effect of Moisture Content

Once a dryer has been built, there are some fixed operating parameters and some variable ones. The variable ones include

- moisture content of the green chips
- heat input of furnace
- throughput (tonnes/hour) of chips
- final moisture content

A computer modelling of the operation of the dryer revealed that

. the key element in both the cost of drying, and in the value of drying, is the quantity of water removed, rather than the quantity of chips being dried.

. at low rates of furnace energy, the energy recovery aspects of the dryer produce an extremely favourable ratio of furnace energy/quantity of water evaporated, but the other costs remain relatively fixed and become higher on a basis of cost per unit of water.

. work with the computer model led to some promising changes in the sizes of the different sections of the condenser, changes which reduce the size of the condenser and the amount of fan power needed, while increasing the amount of evaporation in the dryer.

. the amount of evaporation expected with the planned 750,000 kJ/hr of furnace heat has increased from 2000 lb/hr as derived from preliminary calculations to over 2600 lb/hr.

. further improvements in output capacity might be achieved by fine tuning of operating parameters, and by using a higher proportion of primary energy.

. the subsequent calculations are based on 2600 lb of water/hour, with the drying cost regarded as a flat amount per pound of water removed, regardless of the mass of chips being dried. These numbers represent reasonable expectations of normal operating conditions.

2.7.4.2 Effect of Moisture Content cont.

Key Operating Costs (at 5,000 hr/yr)

	Per Hour	Per lb. of Water Removed
Operating cost	15.12	0.582 cents
Capital Costs	6.80	0.261 cents
Total cost	21.92	0.843 cents

Moisture Content wet basis	Ratio of Water/ solids	Total Water Removal per lb.solids	Total Drying Cost c/lb. solids @ .695 c/lb.water	Incremental Cost/ 5% more drying
50	1	0	----	
45	.818	.182	153	
40	.667	.333	.281	.128
35	.5385	.4615	.389	.108
30	.4285	.5715	.482	.093
25	.3333	.6667	.562	.080
20	.25	.75	.632	.070
15	.176	.824	.695	.063
10	.111	.889	.749	.054

2.7.5 Costs of Drying Tree Chips by Alternative Drying Systems

Figure 1 provides relative capital costs of dryers used for Wet Hog Fuel. These data were developed by Sandwell.

Figure 2 displays data from a study for Pacific Wood Fuel, which operates a wood diversification plant in Lakeview, Oregon.

The raw material used was green sawdust and woodwaste from log debarking. High moisture contents caused problems - especially in the water when the material could not sufficiently air dry. Tests showed moisture of raw material with 110% MC dry basis (54% wet basis). This decreased to 80% MC dry (44% wet basis) after covered storage.

The study considered capital and operating cost of three sizes of facilities - heated by oil or gas, woodwaste, and geothermal. These calculations indicate that the woodwaste facilities would have operating costs of about 40% of oil or gas fired facilities. In turn, in special situations where geothermal heating could be used, operating costs would be about 40% of woodwaste fired facilities.

Data for the IEC dryer are superimposed on Figures 1 & 2.

2.8 STORAGE COSTS

Section 4.0 of CREDA Project #2023 provides some information in small storage units. A collapsible bin holds 88m , or 12 to 18 tonnes of 20% M.C. chips, and was estimated to cost $981.78. This was found to require considerable labour to load and unload. Therefore proper loading and unloading equipment would minimize this.

That report also provides $1,200 costs for an in-ground home storage bin. This bin holds about 13m (480 ft).

Allowing for extra costs for material handling and savings because of increased size, take the cost of large storage at $981.78 for 15 tonnes - or about $65/tonnes. Amortizing this cost over 5 years means about $16.25 per tonne stored.

Consider that the plan works all year and therefore 2/3 of production must be stored 6 months. The storage must be capable of storing 4 tonnes/hr x 5000 hr x 2/3 or 13,333 tonnes. The amortized storage container would be $216,667. Over the total production, this would cost $10.83/tonne.

To this must be added the interest cost of the chips stored. Consider that chips costs $26.83/green tonne plus $7.08/ tonne (typical) for drying to give a total cost of stored chips at $33.91/tonne. Interest cost would therefore be 13,333 x 33.91 x .12 x 6/12 = $27,127 total or $1.36/tonne of total production.

Storage costs therefore would be $12.19/tonne.

2.9 TOTAL COSTS OF TREE CHIPS INCLUDING DRYING

Table 11 provides data on the cost elements and the total costs of chips. This table is developed using two assumptions:

1. Green chips are obtained from thin operations. Further, the cost of cutting is charged to the woodlot.
2. The average moisture content of green chips is 36.4%. (Average of two thin test data in CREDA #2023.)

   The delivered costs of wood chips range from $51.30 to $70.28/tonne.

The above is based on a cost of $26.83/green tonne delivered to the dryer. This assumes that thin operations would provide sufficient material to supply anticipated markets. If material had to be obtained from several sources, the price would rise to $106.56/green tonne (as reported in CREDA #2023). This gives a corresponding delivered cost of $131.03 (40 to 60% M.C.) to $190.64 (at 10% M.C.)/tonne. (See Table 12 for details).

2.10 EFFICIENCY OF BURNING

Moisture content of wood chip fuel affects boiler efficiency in two main ways:

1. Heat energy must be used to evaporate the water, and
2. more excess air must be used to help dry the fuel.

2.10.1 Evaporating Water

Table 13 shows the heat loss to evaporate the water and to heat the water vapour to flue gas temperature. The heat demand is based strictly on the enthalpy required to heat the water/gas to the flue gas temperature. But, for a given weight of fuel, the amount of heat available is reduced proportionately to the quantity of dry wood chips available. The heat loss of three to four percent is insignificant at 20% moisture content, but rises to use about one-fifth of the heat available at 60% moisture content.

Note that the data of this table match Figure 1 of C. MacCallum et al (Ref. No. A).

2.10.2 Excess Air

C. MacCullum et al (Ref. No.A, p.6) discuss the excess air requirement. They note the relationship between fuel moisture content and excess air requirement is not well defined. They discuss some available data. From data of their first reference, they estimate that at 28 and 63 percent moisture levels, the use was 30 and 80 percent excess air respectively. A second reference suggested the percentage of excess air was typically about twice the percentage moisture content of hog fuel. Two other references suggested that the percentage of excess air is typically about equal to the percentage moisture content of hog fuel, on a wet basis.

Continuing, MacCallum et al note that design data in a number of boiler bids from various manufacturers indicate that, for moisture contents in the range 50 to 65 percent, anticipated use of excess air in the furnaces would range from 25 to 34 percent! The authors then note that these data represent boiler manufacturers' experience of values that can be achieved with care - but not necessarily so in day-to-day practice.

2.10.3 Boiler Efficiency

Figure 7 is adapted from MacCallum et al Ref A Fig.7. This shows the effect of Moisture on Boiler Efficiency. The total efficiency line is MacCallum et al. We added curves to show the loss due to moisture in chips and due to excess air. Other losses include radiation, incomplete mixing of air and fuel, excess air to compensate for incomplete mixing, heating the dry component of the fuel, pyrolysis of the dried fuel, etc.

Also shown is a typical Black-out Area where supplementary fuel (oil or natural gas) is required to keep the burning process going.

2.10.4 Heat Output

Figure 8 combines the boiler efficiency data of figure 7 and the heating capacity data from Table 13.

At a theoretical zero percent moisture content burning inefficiencies would use aabout 20 percent of the available heat.

At a more realistic value of 20 percent moisture content a given weight of wood chips would have only 80 percent fuel and a burning efficiency of about 60 percent.

At 60 percent moisture content the boiler efficiency is less than 60 percent and the wet wood chips contains only 40 percent fuel by weight. As a result, the calculated boiler output would only be some 2000 BTU/lb of wood chip fuel fired. This is only 23 percent of the theoretical heat in a pound of dry wood chips.

2.10.5 Steam Generating Capacity

MacCallum et al also reported the strong dependant of boiler evaporation on fuel moisture content.

They cite the results of a boiler test by R.C.Johnson at Weyerhauser Company in Longview, Washington. By decreasing the hog fuel moisture content from 67 to 28 percent (wet basis), the steam production in this actual boiler was almost doubled (8.9 kg/s to 13.7 kg/s). Johnson also found there was essentially no increase in flue-gas rate associated with that increased steam production. Therefore, where a boiler is limited by supply air, furnace gas residence time, or air pollution abatement system, a reduction of fuel moisture content will greatly increase steaming capacity.

2.10.5 Steam Generating Capacity cont.

Sandwell personnel observed steam generating capacity at a paper mill, with bark at 50 and 60 percent moisture, (and supplementary out) the boiler can generate 55,000 and 45,000 kg/h respectively. Of this some 50,000 and 27,000 kg/lb respectively came from the hog fuel.

MacCallum et al also reported on theoretical and boiler test data by Mekantransport AB. These data indicate a greater increase in the 60 to 70 percent range. Obviously steam or heat output is sensitive to furnace design and very sensitive to moisture content of the fuel.

Finally, MacCallum et al provided a chart showing on an ordinary scale, the change in steam (heat) production expected from a change in fuel moisture content. Below 15% moisture content, they suggest pulverized firing could be used - as is done with coal. Above 15% moisture content, combustion would be done by grate firing. Because of its importance, this chart is reported herein as figure 9.

Reference A.C. MacCallum, B.R. Blackwell, L. Torsein, "Cost Benefit Analysis of Systems using Flue Gas or Steam for Drying of Wood Waste Feedstocks", Final Report DSS Contract 42 SS KL 229-0-4002, ENFOR Project C-96, Contractor: Sandwell & Company Ltd., Suite 601, 1550 Alberni Street, Vancouver, V6G 1A4. Scientific Authority: Mr. R.J. Neale, Canadian Forestry Service, 19th Floor, Place Vincent Massey, 351 St. Joseph Blvd., Hull K1A 1G5.

2.11 HEAT ENERGY FROM BURNING TREE CHIPS WITH VARIOUS MOISTURE CONTENTS

Table 14 provides costs data for green chips delivered to the dryer dry chips, stored dry chips, delivered chips, and heat energy. Costs of heat energy from burning range from \$11.24/million BTU using 60% M.C. chips to \$5.10/million BTU using 10% M.C. chips.

These data are illustrated on figure 10. For comparison, data for electricity is shown. Electricity would be considerably higher cost for heat energy, even if it could be obtained for an unrealistically low 4.0 cents/kWh.

2.12 OBSERVATIONS AND DISCUSSIONS

The Project

1. This project evaluated the economic potential of burning wood chips for space heating.

2. The study combined information from the literature with data gained by design of a high efficiency dryer.

3. Literature data on the cost of green wood chips varied widely with calculated estimates being about one-quarter the costs determined by field tests.

Cost of Chips

4. Green chips gathered from all types of operations (clear, slash, and thin combined) are too expensive.

5. Green chips obtained from thin operations, where only the cost of chipping and delivery to the dryer is charged to the chips, appears viable. It is believed that sufficient chips can be obtained in this way to satisfy near-future markets.

6. Drying costs is a small portion (0 to 11%) of the cost of delivered wood chips.

Burning Efficiency

7. Fuels above about 68% moisture content (M.C.wet) causes furnaces to black out.

8. It is desirable to keep fuels below 24 M.C. to prevent freezing and fungal problems.

9. Boiler efficiencies are affected by moisture in the wood chips by excess air, and by a variety of other losses.

10. Moisture in the wood chips is insignificant while using low M.C. fuels but it is the major loss at high M.C.

11. Excess air is required to ensure complete combustion. With increased M.C., the moisture from the wood chips dilates the oxygen properties and forces an increase in excess air.

12. Other losses include radiated heat, heat up the stack etc.

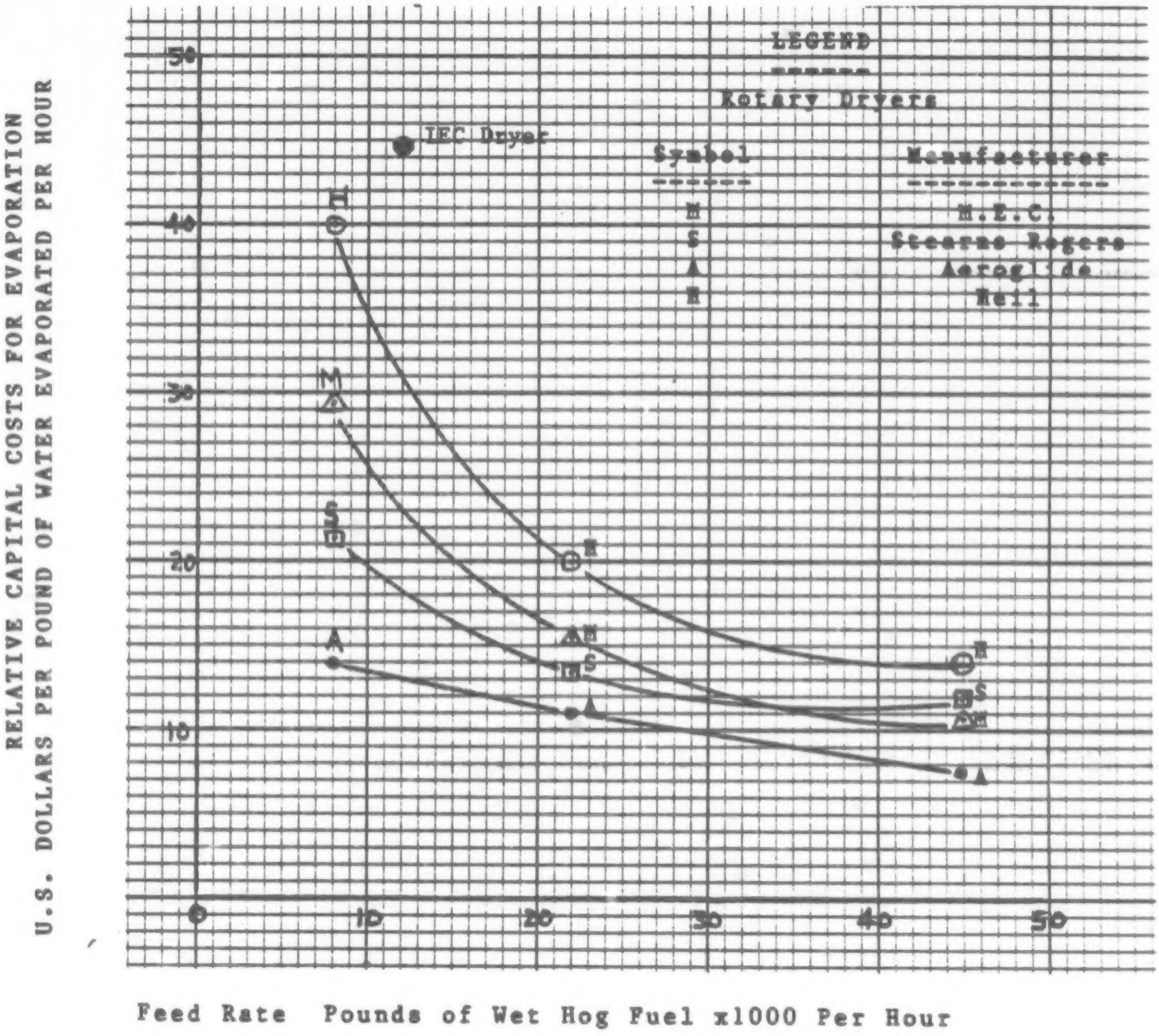
13. Boiler efficiency ranges from about 53 to 80%.

14. Costs per million BTU ranged from $5.10 to $11.24.

2.13 FIGURES & TABLES

Figure 1

EFFECT OF SIZE OF DRYER ON
RELATIVE CAPITAL COST FOR EVAPORATION

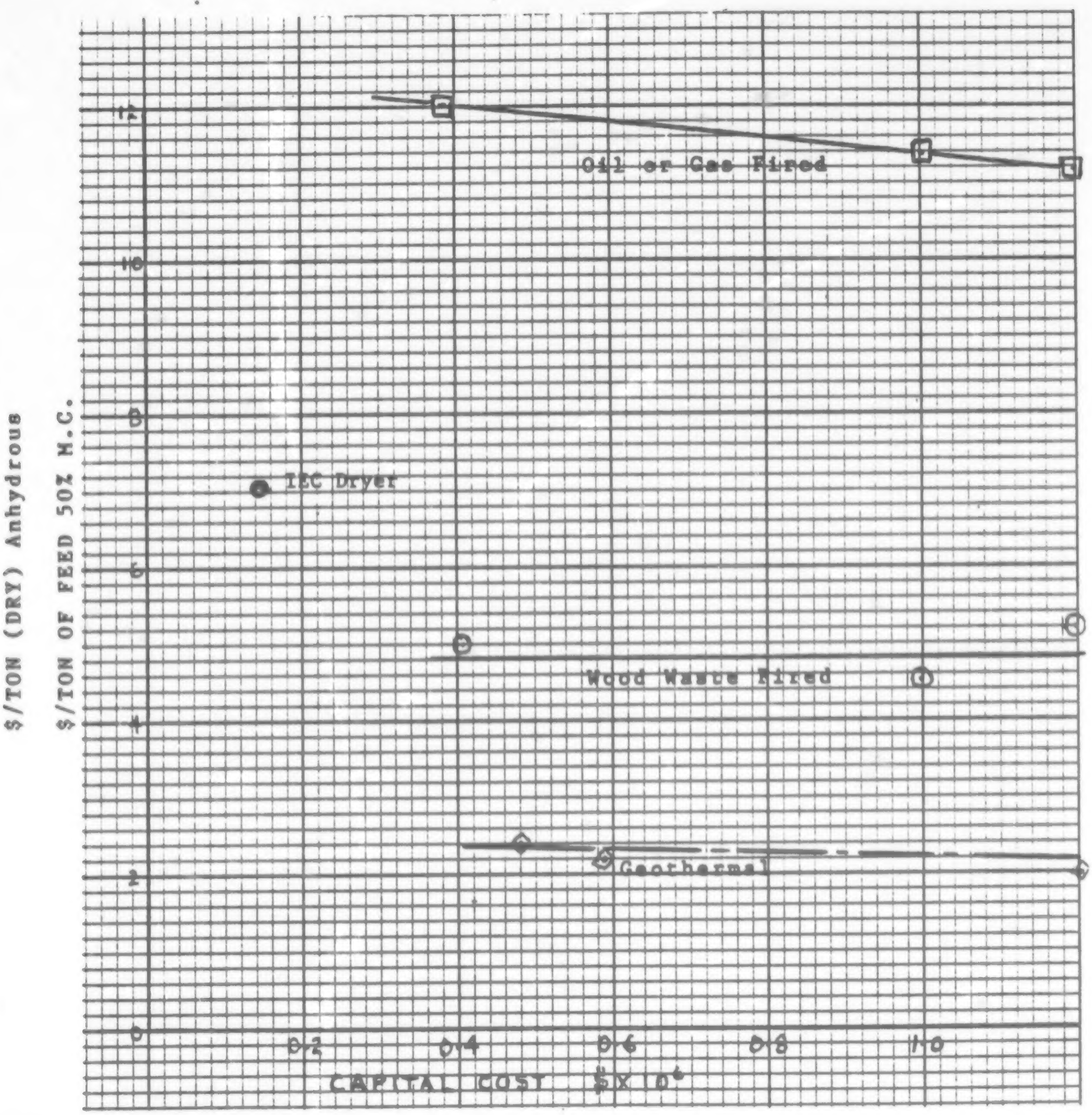


Notes:

1) H Units include air heater and burner
2) Reference - The Utilization of Forest Biomass and Forestry Industry Waste for the Production and Conservation of Energy.

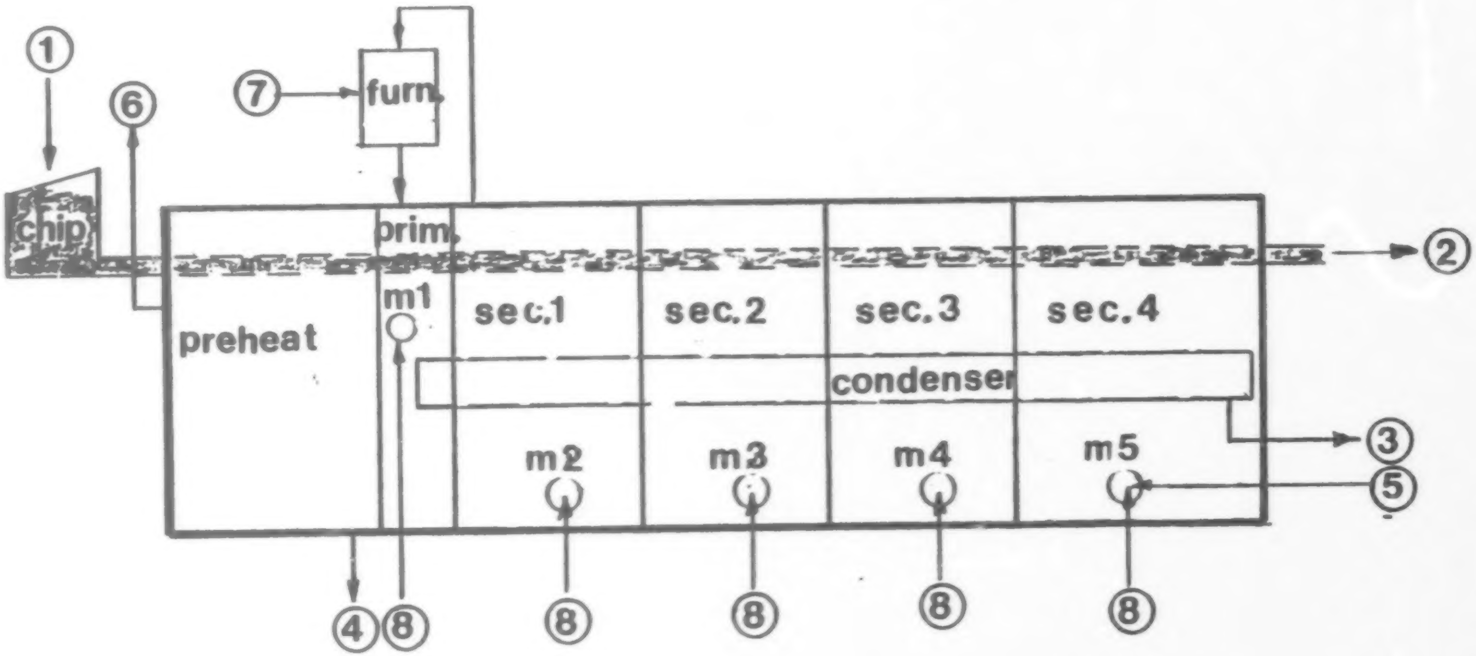
FIGURE 2

Effect of Size on Operating Costs per Ton



Ref: An Engineering Study of the Use of Geothermal Energy to Dry Wood Waste for Densification. Dynamic Systems Inc., Jan. '81 Job #2915

Figure 3


①
chip
⑥
⑦
furn.
prim.
m1
preheat
sec.1
sec.2
sec.3
sec.4
condenser
m2
m3
m4
m5
②
③
⑤
④
⑧
⑧
⑧
⑧
⑧

TREE CHIP DRYER — EMR

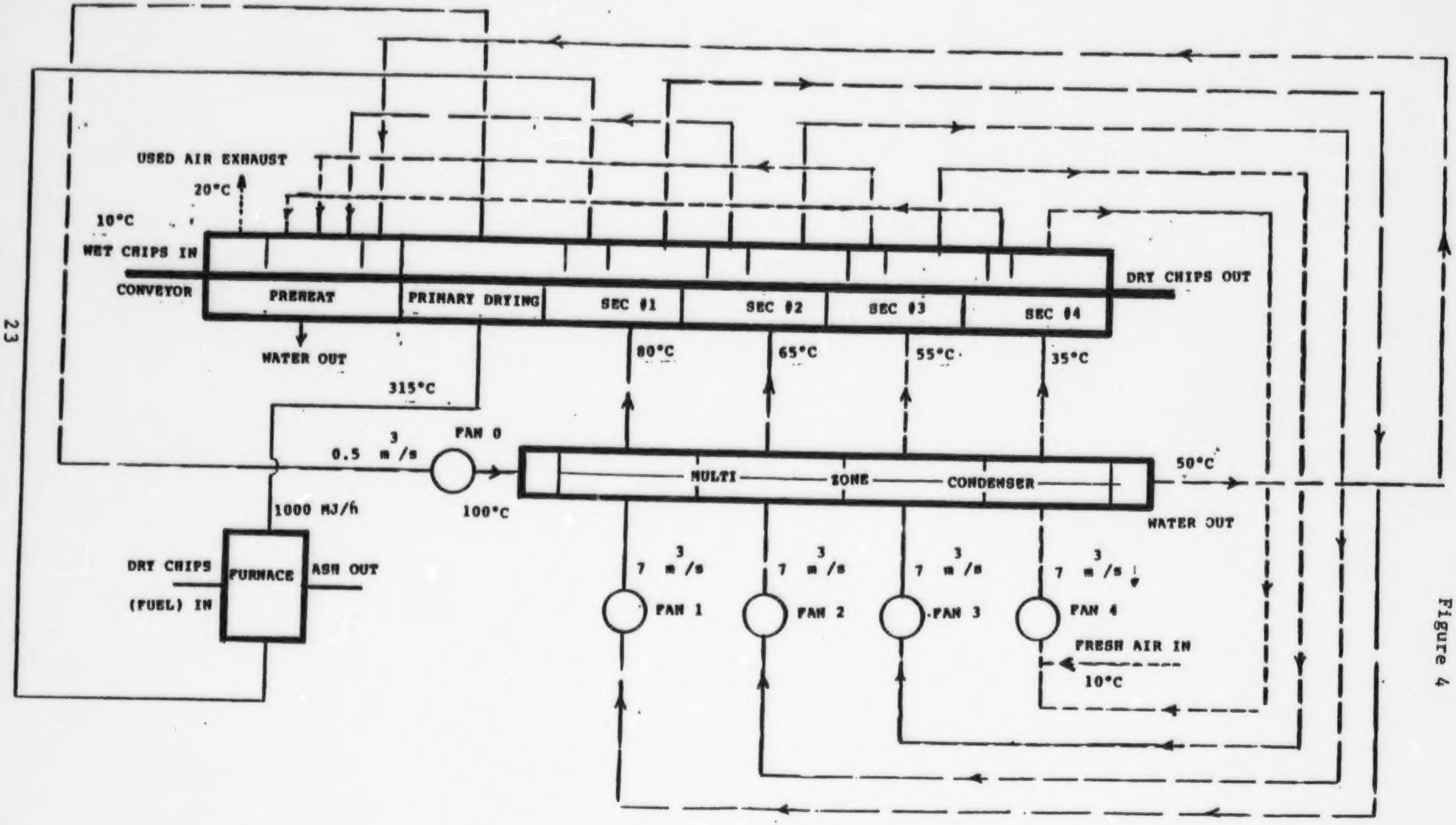
SCALE:	APPROVED BY:	DRAWN BY
DATE:		REVISED

MASS & ENERGY FLOW DIAGRAM

IEC –TCD–FS–A –24

DRAWING NUMBER

Figure 4


USED AIR EXHAUST
20°C
10°C
WET CHIPS IN
CONVEYOR
PREHEAT
PRIMARY DRYING
SEC #1
SEC #2
SEC #3
SEC #4
DRY CHIPS OUT
WATER OUT
315°C
80°C
65°C
55°C
35°C
FAN 0
0.5 m³/s
100°C
MULTI ZONE CONDENSER
50°C
WATER OUT
1000 MJ/h
DRY CHIPS (FUEL) IN
FURNACE
ASH OUT
7 m³/s
FAN 1
7 m³/s
FAN 2
7 m³/s
FAN 3
7 m³/s
FAN 4
FRESH AIR IN
10°C

EMR - IEC TREE CHIP DRYING SYSTEM
(with heat recovery)

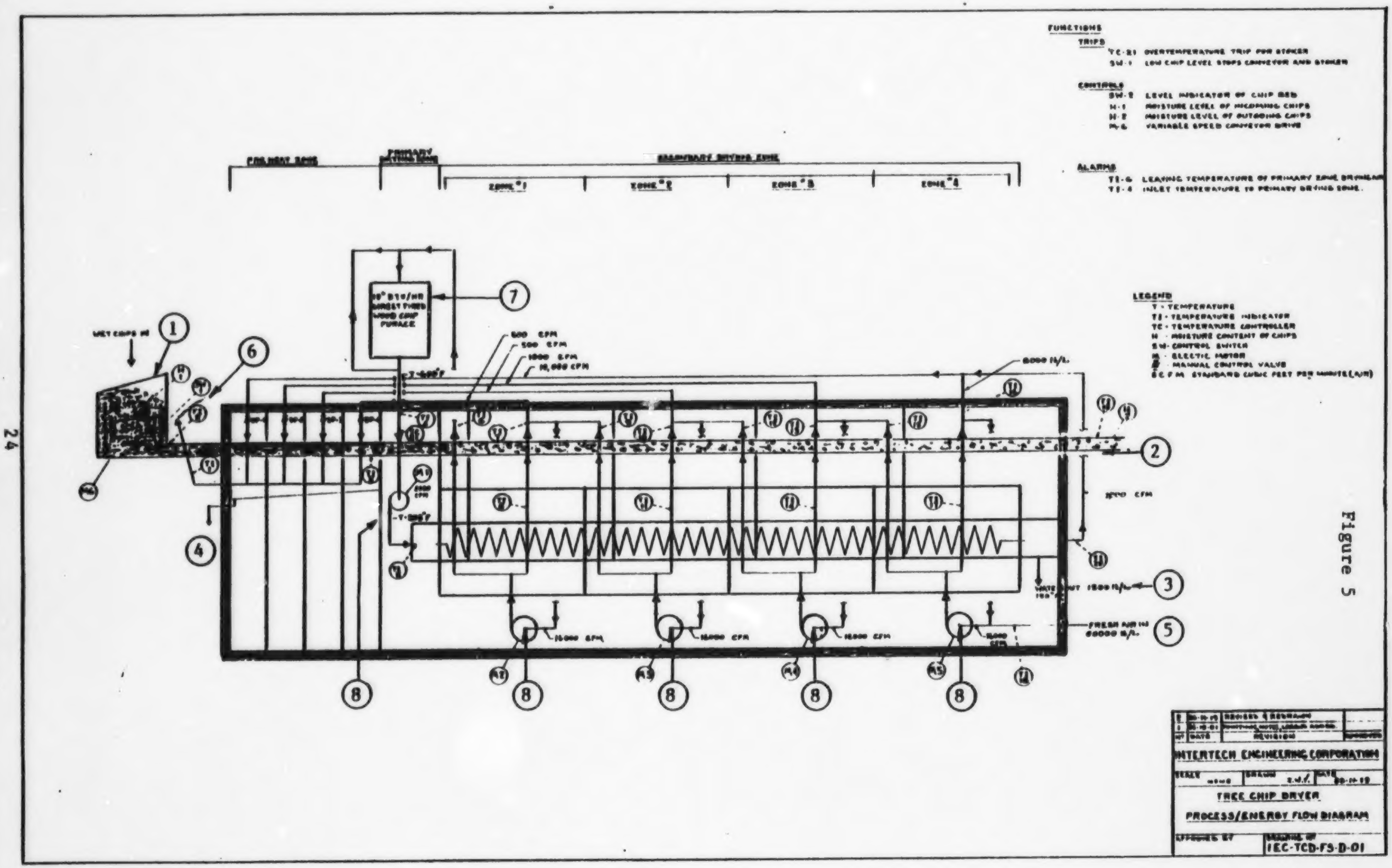

PREHEAT ZONE
PRIMARY DRYING ZONE
SECONDARY DRYING ZONE
ZONE #1
ZONE #2
ZONE #3
ZONE #4
WET CHIPS IN
1
2
3
4
5
6
7
8
10^6 BTU/HR DIRECTLY FIRED WOOD CHIP FURNACE
T-600°F
600 CFM
500 CFM
1000 CFM
10,000 CFM
2000 CFM
16000 CFM
6000 lb/hr.
WATER OUT 1500 lb/hr
FRESH AIR IN 60000 lb/hr.
M-1
M-2
M-3
M-4
M-5
M-6
FUNCTIONS
TRIPS
TC-21 OVERTEMPERATURE TRIP FOR STOKER
SW-1 LOW CHIP LEVEL STOPS CONVEYOR AND STOKER
CONTROLS
SW-2 LEVEL INDICATOR OF CHIP BED
M-1 MOISTURE LEVEL OF INCOMING CHIPS
M-2 MOISTURE LEVEL OF OUTGOING CHIPS
M-6 VARIABLE SPEED CONVEYOR DRIVE
ALARMS
TI-6 LEAVING TEMPERATURE OF PRIMARY ZONE DRYING AIR
TI-4 INLET TEMPERATURE TO PRIMARY DRYING ZONE.
LEGEND
T - TEMPERATURE
TI - TEMPERATURE INDICATOR
TC - TEMPERATURE CONTROLLER
M - MOISTURE CONTENT OF CHIPS
SW - CONTROL SWITCH
M - ELECTRIC MOTOR
MANUAL CONTROL VALVE
SCFM STANDARD CUBIC FEET PER MINUTE (AIR)
REVISED & REDRAWN
REVISION
DATE
APPROVED
INTERTECH ENGINEERING CORPORATION
SCALE NONE
DRAWN
DATE
TREE CHIP DRYER
PROCESS/ENERGY FLOW DIAGRAM
APPROVED BY
DRAWING NO.
IEC-TCD-FS-D-01

Figure 5

TREE CHIP TRANSPORT COSTS

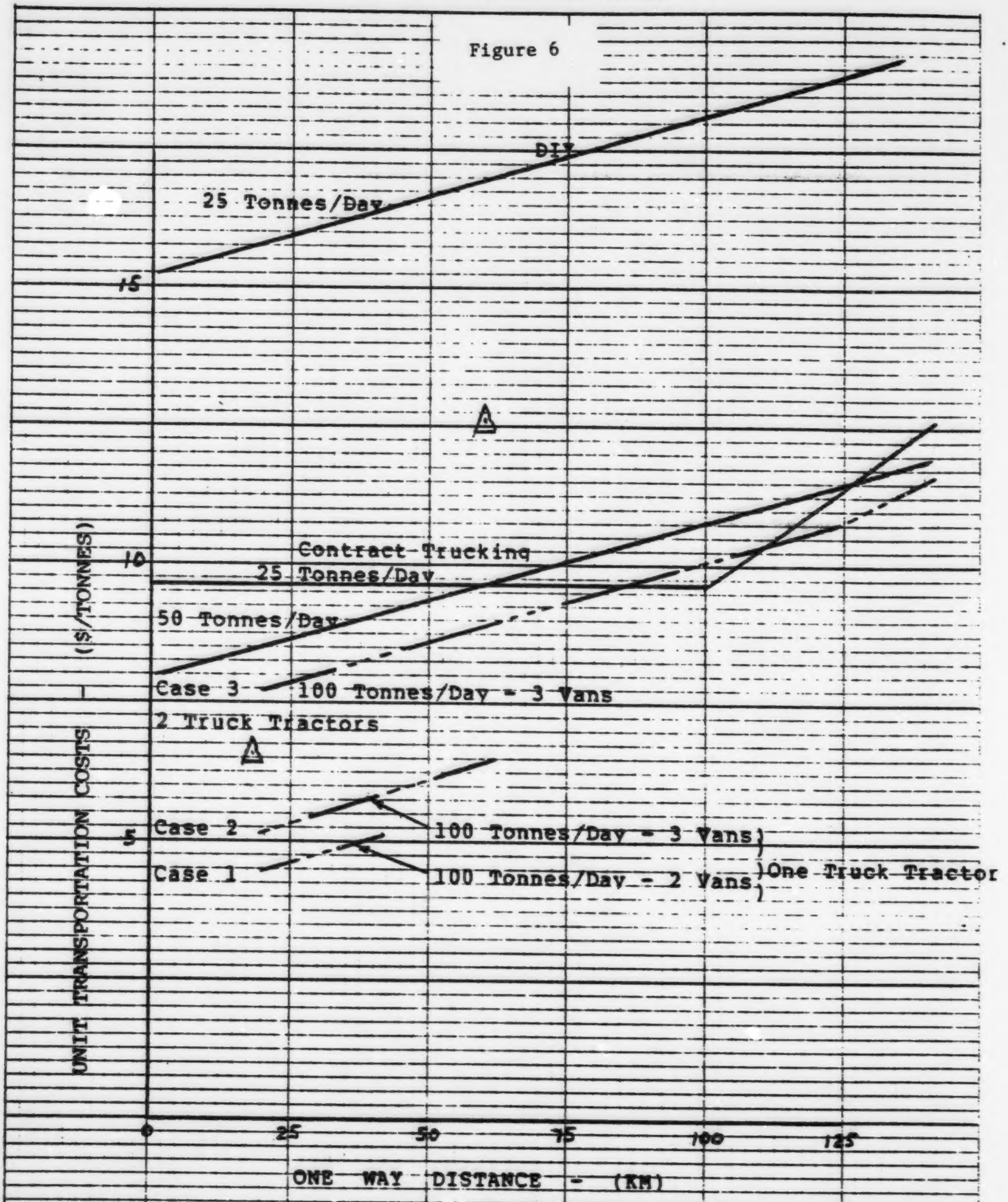
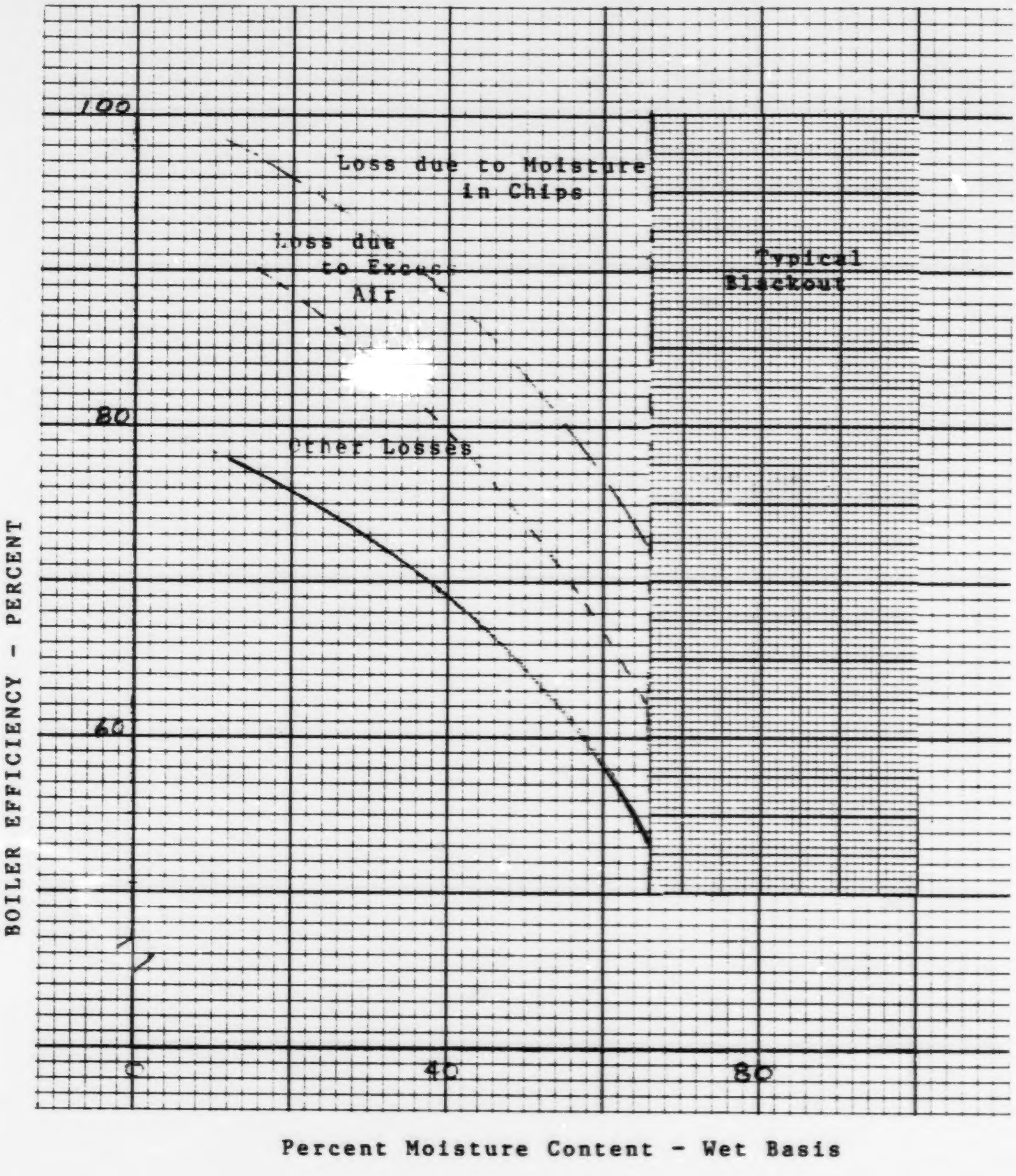


Figure 6

Ref: ENFOR Project P-302 Configuration of Small Scale Biomass Harvesting and Transport Systems by Kipping & Associates Ltd.

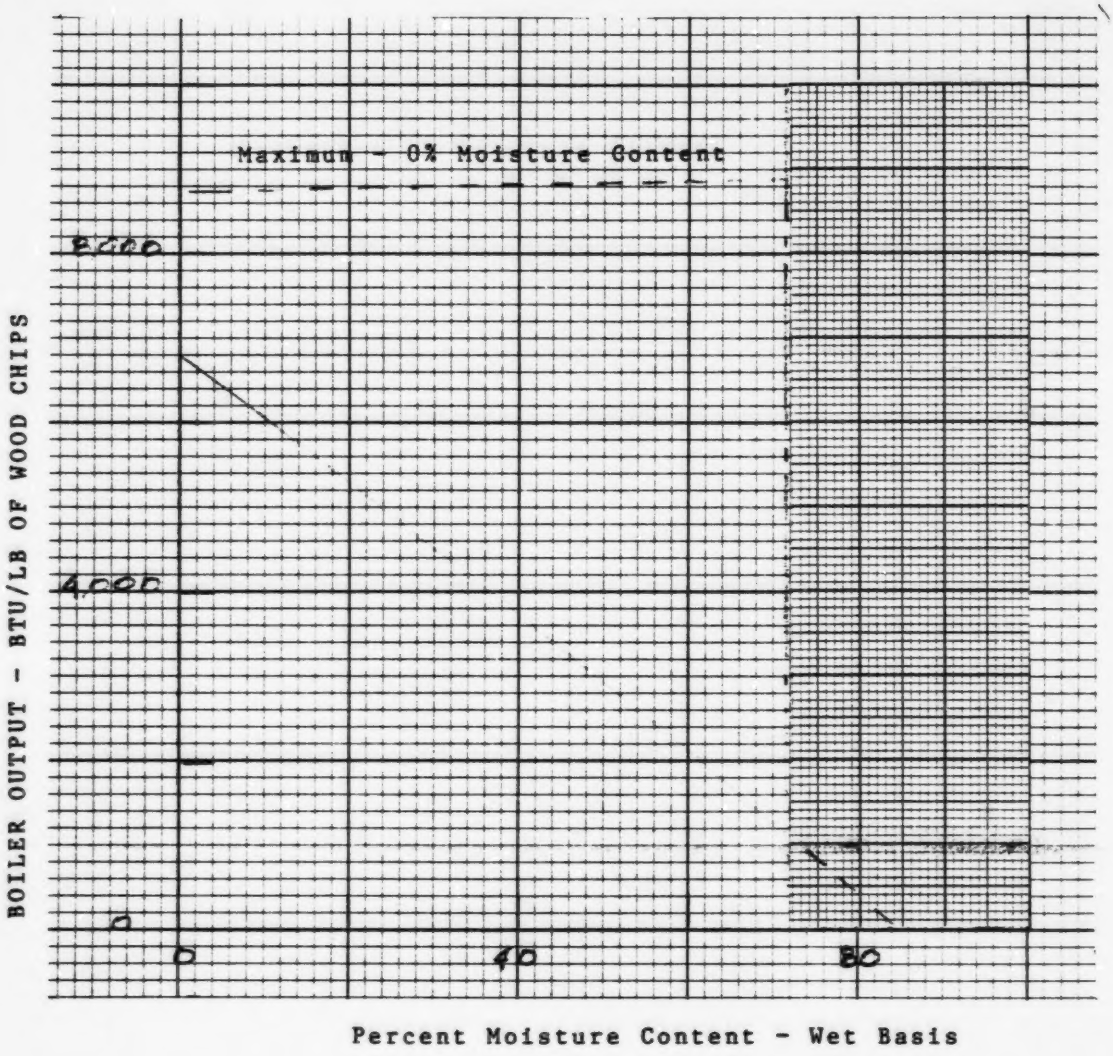
Ref: △ CREDA Project #2023

Figure 7



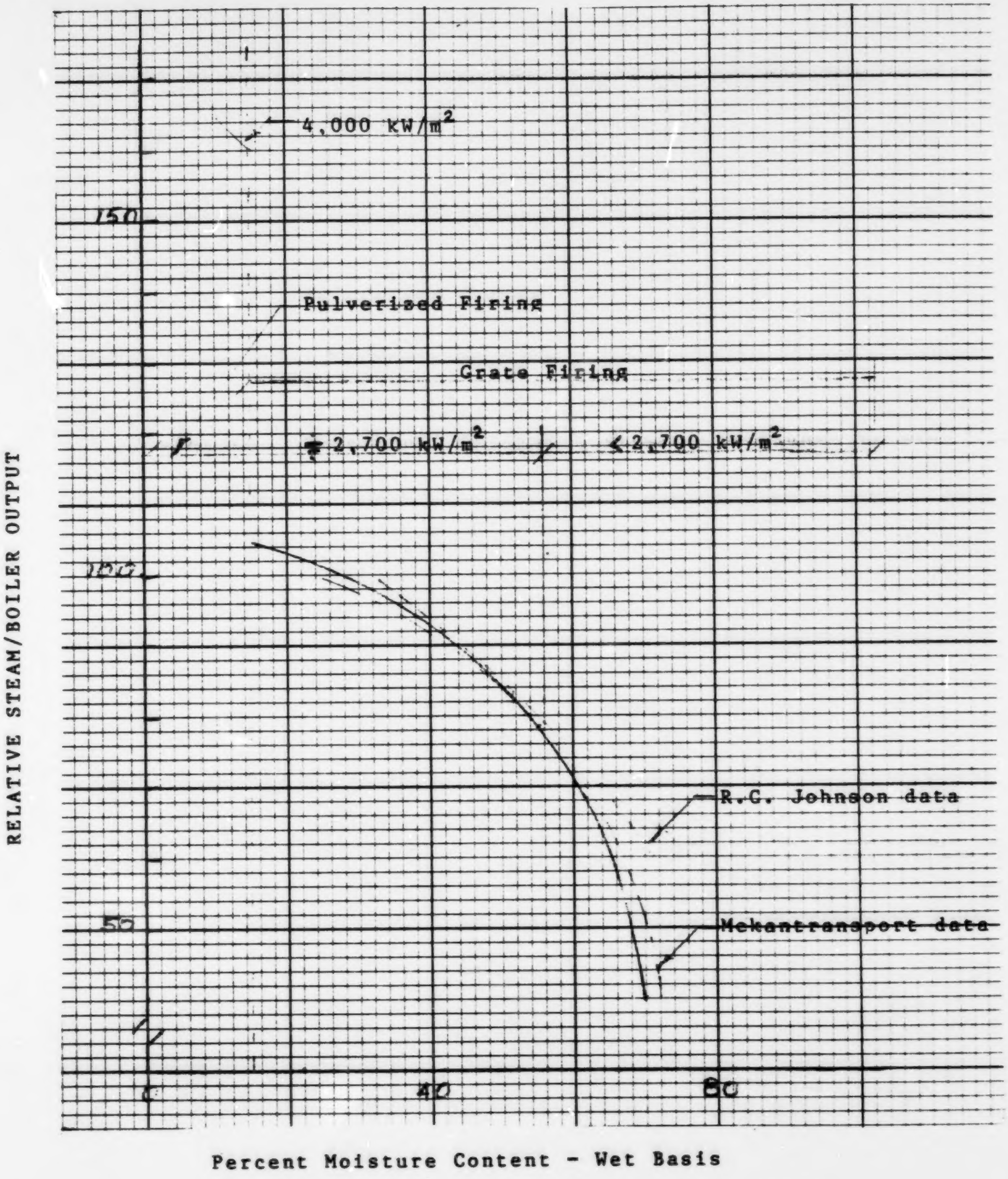
Wood Chip Moisture Content Effect on Boiler Efficiency

Figure 8



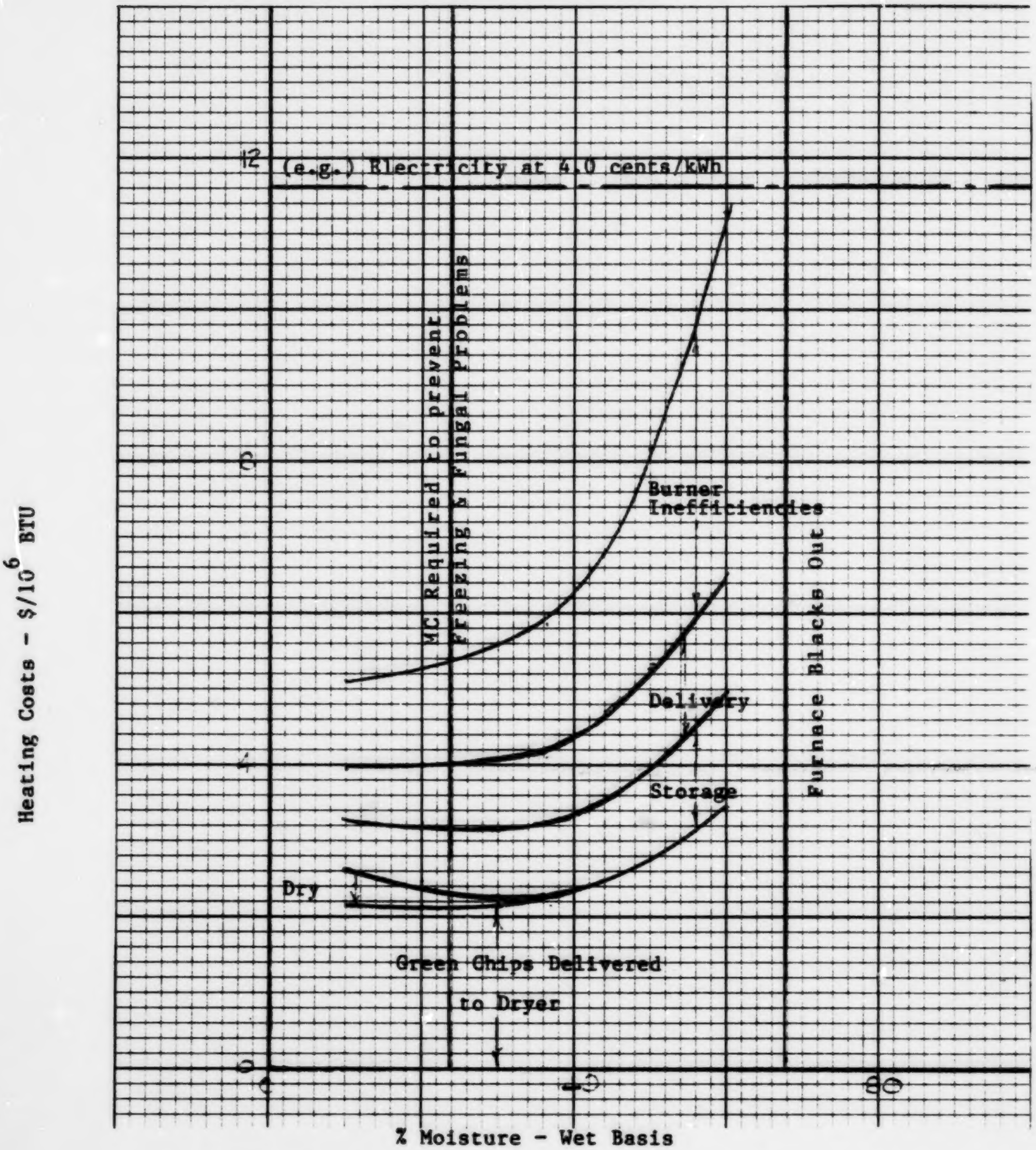
Wood Chip Moisture Content Effect on Boiler Output

Figure 9



Relationship of Wood Chip Moisture to Effect of Steam/Boiler Output

Figure 10



Effect of % Moisture on Heating Costs

TABLE 1: SPECIFIC WEIGHT/SPECIFIC VOLUME FOR WOOD

As produced chip bulk density

Hardwood	320 Kg/M^3	20 lbs/ft^3
Softwood	250 Kg/M^3	16 lbs/ft^3

20% M.C. chip bulk density

Hardwood	240 Kg/M^3	15 lbs/ft^3
Softwood	200 Kg/M^3	12 lbs/ft^3

Average Volume Expansion Ratios

Solid Wood to chips	2.6
Cordwood to chips	1.7

Ref: Small Scale Wood Chip Fuel - Harvesting and Processing, University of New Brunswick, M.H. Schneider et al, CREDA Project #2023

TABLE 2: PROPERTIES OF WOOD

Name of Species	Moisture Content %	Specific Gravity[3]
Ash, commercial white[4]	43	.54
	12	.58
Cedar, Alaska	38	.42
	12	.44
Cedar, eastern red	35	.44
	12	.47
Cedar, northern white	55	.29
	12	.31
Cedar, western red	37	.31
	12	.33
Douglas fir,(coast region)	36	.45
	12	.48
Douglas fir, (Rocky Mountain region)	38	.40
	12	.43
Elm, American	89	.46
	12	.50
Elm, rock	48	.57
	12	.63
Pine, northern white	68	.34
	12	.36
Pine, Norway	54	.44
	12	.48
Pine, western white	54	.36
	12	.38
Poplar, yellow	64	.38
	12	.40
Spruce, eastern[5]	46	.38
	12	.40

Table 2: Properties of Wood cont.

Notes

1. Test specimens 2 by 2 in. in section.

2. The values in the first line for each species are from tests of green material; those in the second line are from tests of seasoned material adjusted to an average air dry condition of 12 percent moisture.

3. Based on weight when oven dry and volume when green or at 12 percent moisture content

4. Average of Biltmore white ash, blue ash, green ash, and white ash.

5. Average of black spruce, red spruce, and white spruce.

Source: From Wood Handbook, U.S. Department of Agriculture, prepared by Forest Products Laboratory, Madison, Wis. (Results of tests on small,[1] clear specimens in the green and air-dry condition[2])

TABLE 3: CALORIFIC VALUE OF CHIPS AT VARIOUS MOISTURE CONTENTS, WET WT. BASIS

The following table shows how the calorific value of chips is reduced by the dilution effect of including various moisture contents in the mass of fuel, starting with a calorific value of 8750 BTU per lb. of solids.

Moisture Content Wet Basis	Ratio of Moisture/Solids	Calorific Value BTU/wet lb.
10%	.11	7875
20%	.25	7000
30%	.43	6125
40%	.667	5250
50%	1.0	4375
60%	1.5	3500

TABLE 4: ESTIMATED COSTS OF GREEN CHIPS
$1985/TONNE

Ref.Table	Tonne/day	Fell&skid	Chip	Transport	Misc.	Total
4.1	25	$10.70	$10.04	$9.60	4.84	35.18
4.2	50	6.58	5.22	10.50	2.92	25.22
4.3	60	5.82	4.63	9.00	2.43	21.88
4.4	50	9.52	5.22	10.80	2.93	28.47
4.5	100	5.87	5.01	10.49	2.10	23.47
4.6	100	5.72	5.01	10.49	1.96	23.18
4.7	120	5.81	5.09	8.74	1.67	21.31
Average		7.15	5.75	9.94	2.69	25.53

Ref: ENFOR Project P-302, Configuration of Small Scale Biomass Harvesting and Transportation Systems, Kipping & Associates Ltd. June 1985

Note: P6 of Ref notes that the solid volume content of whole-tree chips is assumed to be 40%.

TABLE 5a: ESTIMATED COSTS OF CHIPS (20% MC)
$1985/TONNE

Ref.Table	Labour Man Hours	Labour Cost	Field Equipt	Chipping Equipt	Transport	Total	$/10 MBTU
7.4	16.43	121.61	43.14	6.69	26.77	198.21	12.64
7.7	6.24	46.15	30.90	7.26	19.79	104.10	6.64
7.13		---------	Average of 9 Tests		--------	148.79	9.49

Ref: CREDA Project #2023 - Small Scale Wood Chip Fuel Harvesting and Processing, U. of New Brunswick, Feb 1985

TABLE 5b: ESTIMATED COSTS OF CHIPS - WET BASIS

Block	Green Tonnes Chips Produced	Average M.C.-%	Average Stand Diameter - CM	Total Costs $ 1985	Cost/Green Tonne $ 1985
Slash 1	15.8	45	NA	1,791.64	113.39
Slash 2	NA	NA	NA	1,465.02	---
Thin 1	17.9	44	5.6	2,961.20	165.43
Thin 2	49.0	73	13.9	4,836.97	98.71
Clean 1	21.4	91	9.2	2,226.61	104.04
" 2	21.4	88	7.0	1,418.88	66.30
" 3	15.7	87	7.2	1,649.71	105.08
" 4	20.6	78	7.2	2,656.54	128.96
" 5	23.2	81	6.9	1,638.23	70.61
				Avg.	106.56

Ref: CREDA Project #2023 - Small Scale Wood Chip Fuel Harvesting & Processing - U. of New Brunswick, Feb.'85, Tables 2.1, Tables 7.2 through 7.10.

TABLE 6: TREE CHIP DRYER

MASS FLOW RATES FOR AIR AND WATER AT A NOMINAL OPERATING CONDITION

REFER TO DRAWING NO. IEC-TCD-FS-A-24

LOCATION	MASS FLOWS POUND PER HOUR	
	WATER	DRY AIR
1) INLET OF CHIPS TO DRYER	5400	NA
2) OUTLET OF CHIPS FROM DRYER	2800	NA
3) LIQUID RECOVERY FROM CONDENSER AND COOLING IN SECONDARY SECTION	2000	NA
4) LIQUID RECOVERY FROM PREHEAT	600	NA
5) FRESH AIR INLET TO M5	270	35,000
6) OUTLET AIR FROM PREHEAT	680 *	35,000

* Vapour

NOTES:

(a) Flow rate of anhydrous wood chips ....6600 pounds per hour
(b) Specific heat of anhydrous wood chips.......0.6
(c) Inlet temperature of wood chips.........50°F
(d) Outlet temperature of wood chips........72°F
(e) Heat loss of chips = (22x0.6x6600)+(22x1.0x3070) = 154,660
(f) Temperature of condensate at location (3)......115°F, BTU/hr.
(g) Heat loss of condensate at location (3)......65,000 BTU/hr.
(h) Temperature of inlet air at location (5)........50°F
(i) Temperature of air leaving preheat (Loc.6)......77°F
(j) Temperature of air inlet to furnace (Loc.7)....170°F
(k) Flow rate of wood chips to furnace (Loc.7)..150 pounds per hour
(l) Outlet heat from furnace to dryer...........750,000 BTU/hr.

TABLE 7: ENERGY FLOW LEGEND

PROCESS ENERGY FLOW DIAGRAM IEC-TCD-FS-D-01

1) Wet tree chips into dryer
2) Dried tree chips from dryer
3) Liquid collection from condenser
4) Liquid collection from preheat section
5) Fresh air inlet to blower M5 on secondary of final stage of condenser
6) Air outlet from wet tree chips inlet hopper
7) Fuel (dried tree chips) input to furnace
8) Electrical input to drive motors on blowers M1, M2, M3, M4, M5.

TABLE 8: TREE CHIP DRYER

ENERGY FLOW RATES AT A NOMINAL OPERATING CONDITION

REFER TO DRAWING NO. IEC-TCD-FS-A-24

LOCATION	ENERGY FLOWS BTU PER HOUR			
	CHIPS	AIR	WATER	ELECTRICAL
1) INLET OF CHIPS TO DRYER	(a)	NA	97,200	NA
2) OUTLET OF CHIPS FROM DRYER	(a)	NA	112,000	NA
3) LIQUID RECOVERY FROM CONDENSER	NA	NA	65,000	NA
4) LIQUID RECOVERY FROM PREHEAT	NA	NA	51,600	NA
5) FRESH AIR INLET TO M5	NA	420,000	280,000	NA
6) OUTLET AIR FROM PREHEAT	NA	630,000	52,800	NA
7) INLET CHIPS TO FURNACE	800,000	NA	NA	NA
8) POWER TO FANS M1	NA	NA	NA	17,065
M2	NA	NA	NA	27,307
M3	NA	NA	NA	51,201
M4	NA	NA	NA	51,201
M5	NA	NA	NA	51,201
			=	197,975
9) ESTIMATED SYSTEM LOSSES				

NOTES:

a) Each pound of water removed from the wood chips increases the calorific value of the chips on average by 1500 BTU.

∴ increase in heat content of chips is 1500 x 2600 = 390,000 BTU/hr

b) Total energy input to system = 800,000 + 197,975 = 997,975 BTU/hr.

c) Ratio of energy increase to energy input = $\frac{3,900,000}{997,975} = 3.91$

TABLE 9: CAPITAL ESTIMATE - IEC DRYER

a) MATERIALS AND COMPONENTS

(i) Structural

Panel Assemblies - includes 4" mineral wool insulation

Outside	16 ga aluminized steel	
Inside	20 ga " "	
Total	2100 sq.ft. @ $14.00/S.F.	$29,400

Structural Steel - assembled

Framework	3600 lbs.	
Base channels	4500 lbs.	
Total	8100 lbs. @ $2.00/lb	$16,200

Internal Zone Partitions - assembled

800 sq.ft. 16 ga. aluminized steel
= 2000 lbs.@ $1.20 lb. $ 2,400

(ii) Heat Exchanger/Condenser Components

(header boxes,intermediate supports & flow guides)
360 sq.ft. 1/8" aluminum plate
and 16 ga. aluminized steel
= 900 lbs @ $3.00 lb $ 2,700

(iii) Conveyor

Steelwork

550 sq.ft. perforated 16 ga. aluminized steel
= 1375 lbs.

2400 lbs supporting steel
1150 lbs 16 ga. aluminized steel

5325 @ 2.00/lb $10,650

Conveyor Drive including controls $ 1,200

Partitions (between conveyor & heat exchanger)
horizontal and vertical

330 sq.ft. 16 ga. al. steel = 825 lbs.
400 ft. 2" x 2" x 1/4" angle 1333 lbs.

$2.00 x 2158 lbs $ 4,316

Table 9: Capital Estimate - IEC Dryer cont.

(iv) Fans & Blowers (Vane Axial Type)	
Circulating Fans not installed	
4 - 15,000 CFM, 1 1/2" S.P. 10 HP 3/60/575V $2,000	$ 8,000
Supply Fan & Primary Circulating Fan not installed	
2 - 5000 CFM, 1 1/2" S.P. 7 1/2 H.P. 3/60/575V $1750	$ 3,500
(v) Condenser Tubes - not installed	
Aluminum with integral fins 145 pcs 1 1/4" bore x 32' long	($10,000) est.
(vi) Burner	
2 - 500,000 BTU/HR. $5000	$10,000
Stoker/Feeder	$ 2,000
(vii) Inlet Hopper	$ 2,000
(viii) Discharge Chute	$ 1,000
(ix) Electrical Control - including panel	$ 8,000
(x) Instrumentation & Controls - including panel	$ 3,000
(xi) Miscellaneous Hardware - Access Platforms - Fasteners - Painting - Caulking + Weatherproofing - Lubrication	
TOTAL COST OF MATERIALS & COMPONENTS	$114,366

b) LABOUR

- Electrical & Control	)100 mh @ $30/hr	
- Assembly of Components	)300 mh @ $30/hr	
- Commissionings and Start Up	)100 mh @ $30/hr	$15,000

Total Estimated Cost..........................$129,366

Contingency 20%...............................$ 25,873

TOTAL $155,239

Above does not include Foundations & Transport

TABLE 10: OPERATING ESTIMATE - IEC DRYER

Energy

The budgeted energy input for a dryer that removes one tonne of water per hour is

thermal energy (from chip furnace)	750,000 kJ/h
electrical energy (mostly for fan motors)	150,000 kJ/h
Total:	900,000 kJ/h

Based on a nominal value of \$50/t for dried chips and a realized energy of 60% of 20,000 MJ/t, fuelling cost =

750 /20,000 /.6 = \$6.25 /h

Electricity is a nominal 5 cents/kwh and 36 MJ/kwh

.05/3.6 x 150 = \$2.08 /h

Labour

Labour costs are the largest single part of the operating cost, and also the most variable. Although the dryer will be automatic, someone has to attend it part of the time and most jurisdictions require that there be a buddy present when anyone attends moving machines. Consequently, the labour costs can be anything from almost nil up to the full wages of two persons. Good management requires having other work as well for the persons who attend a dryer: a reasonable charge against the dryer would be half of one persons wages, or say \$5.00 per hour.

Maintenance costs are estimated at \$10,000 per year or \$5.00 per hour based on 2000 h/y.

The total of these operating costs is \$18.37/h or \$3.68 per ton of chips.

$750{,}000{,}000 \text{ Joules} \times 9.480 \times 10^{-4} = \text{BTU}$

TABLE 11: TOTAL COSTS OF TREE CHIPS
(FROM THIN OPERATIONS)

		Drying		$/Dry Tonne				
M.C.(%) Wet Basis	Ratio Water/Solids	Water Removed lb of Solids	Total Cost $/lb of Solids	Drying Cost	Green Chips	Storage	Delivery	Total
60	1.5	---	--	--	26.83	12.19	12.28	51.30
50	1	0	--	--	26.83	12.19	12.28	51.30
36.4	.572	0	--	--	26.83	12.19	12.28	51.30
30	.4285	.1435	.001209	1.90	29.54	12.19	12.28	55.91
20	.2500	.322	.002714	4.86	33.76	12.19	12.28	63.09
10	.1111	.461	.003886	7.83	37.98	12.19	12.28	70.28

TABLE 12: TOTAL COSTS OF TREE CHIPS (FROM ALL TYPES OF OPERATIONS)

	Drying				$/Dry Tonne			
M.C.(%) Wet Basis	Ratio Water/Solids	Water Removed lb of Solids	Total Cost $/lb of Solids	Drying Cost	Green Chips	Storage	Delivery	Total
60	1.5	---	--	--	106.56	12.19	12.28	131.03
50	1	---	--	--	106.56	12.19	12.28	131.03
* 40	.6667	---	--	--	106.56	12.19	12.28	131.03
30	.4285	.2382	.00293	6.571	117.32	12.19	12.28	148.36
20	.2500	.4167	.00513	11.495	134.08	12.19	12.28	170.05
10	.1111	.5556	.00684	15.326	150.84	12.19	12.28	190.64

* Average MC from CREDA #2023 Table 3.11 was 41.1% - Taken at 40%

Heat energy cost ((1,000,000 BTU/h/0.69 burner efficiency)/(8750 x .60 x 2240)) x 106.56 = $13.13

Total hourly costs $25.21.

Costs/lb of water removed = 1.231 cents/lb.

TABLE 13: HEAT LOSS ASSOCIATED WITH WATER VAPOUR IN FLUE GAS AS PERCENTAGE OF HIGHER HEATING VALUE OF DRY FUEL

(Wood Chip Heating Value 20 MJ/kg (8750 BTU/lb)

Flue-Gas Temp. °C(°F)	Wood Chip Moisture, Wet Basis	20	40	60
	Heat in llb of Chips	16(7,000)	12(5250)	8(3500)
315°C (600°F)	Enthalpy (1,334.8 BTU/lb Use Superheated Steam @ Atmospheric Pressure)	0.61(267)	1.23(534)	1.84(801)
	% Heat loss	3.8	10.2	22.9
93°C (200°F)	Enthalpy (1,150.4 BTU/lb) Use Dry Saturated Steam, 212°F,Atmospheric Pressure	0.53(230)	1.06(460)	1.59(690)
	%Heat loss	3.3	8.8	19.7

TABLE 14: COSTS PER MILLION BTU OF OUTPUT
(WOOD FROM THIN OPERATIONS)

	Green		Dry		Stored		Delivered		Furnace Efficiency-%	Heat Energy
MC%	$/Tonne	$/10^6 BTU	$/Tonne	$/10^6 BTU	$/Tonne	$/10^6 BTU	$/Tonne	$/10^6 BTU		$/10^6 BTU
60	26.83	3.42	26.83	3.42	39.02	4.98	51.30	6.54	58.2	11.24
50	26.83	2.74	26.83	2.74	39.02	3.98	51.30	5.24	64.3	8.14
36.4	26.83	2.15	26.83	2.15	39.02	3.13	51.30	4.12	70.1	5.87
30	29.54	2.15	31.44	2.29	43.63	3.18	55.91	4.08	72.8	5.60
20	33.76	2.15	38.62	2.46	50.81	3.24	63.09	4.02	75.9	5.30
10	37.98	2.15	45.81	2.60	58.00	3.29	70.28	3.98	78.2	5.10

TABLE 15: COSTS PER MILLION BTU OF OUTPUT (WOOD FROM ALL OPERATIONS)

MC% Wet Basis	Green		Dry		Stored		Delivered		Furnace Efficiency-%	Heat Energy
	$/Tonne	$/$10^6$ BTU	$/Tonne	$/$10^6$ BTU	$/Tonne	$/$10^6$ BTU	$/Tonne	$/$10^6$ BTU		$/$10^6$ BTU
60	106.56	13.58	106.56	13.58	118.75	15.15	131.03	16.71	58.2	28.72
50	106.56	10.87	106.56	10.87	118.75	12.12	131.03	13.37	64.3	20.79
40	106.56	9.06	106.56	9.06	118.75	10.10	131.03	11.14	69.0	16.15
30	117.32	8.55	123.89	9.03	136.08	9.92	148.36	10.81	72.8	14.85
20	134.08	8.55	145.58	9.28	157.77	10.06	170.05	10.85	75.9	14.29
10	150.84	8.55	166.17	9.42	178.36	10.11	190.64	10.81	78.2	13.82

DESIGN OF A TREE CHIP DRYING SYSTEM
PART II OF II

FINAL REPORT

3. FINAL SECTION

3.1 CONCLUSIONS

1. The largest cost element for wood chips would be the cost of cutting and gathering - ranging from $79.73 to $120.36 per delivered tonne. This element must be eliminated by using wood obtained, free of charge, from woodlot thin operations.
2. It is considered that there will be sufficient wood from woodlot thin operations to supply near-future market requirements.
3. Green chips, delivered, would cost $26.83/tonne. If delivered to a central storage facility and subsequently delivered to the furnace owner, green chips would cost $51.30/tonne.
4. Drying is a small portion (say up to 11%) of the total cost of delivered chips.
5. As chips are dried, the cost/tonne, the BTU's/tonne, and the boiler efficiencies, all increase.
6. Drying slashes the cost of wood-chip heating by more than half - from $11.24/million BTU to $5.10 for wood gathered from selected sources and from $28.72 to $13.82 for wood from all sources.
7. These heat energies could be supplied by electricity ranging in price from 1.74 cents to 9.80 cents/kWh. Alternately these energies could be supplied by oil at prices from 12.14 cents to 68.35 cents/litre. These prices are below current prices in the Maritimes.

3.2 RECOMMENDATIONS

1. A demonstration dryer facility should be set up.
2. Green chips from drying should be obtained from thin operations - as discussed in the body of this report.
3. To expand the supply of green chips, further work should be done to cut the cost of gathering wood from slash and thin operations.

3.3 REFERENCES

"Wood Chip Fuel for Residential Use", by Island Energy Associates, Nov. 1981.

"Implementation Planning for Wood Energy in Prince Edward Island", by C. Kirk Brown & Andrew B. Wells, of Institute of Man & Resources, Jan. 1983.

"Survey of Wood Fuel Use in Prince Edward Island 1982-1983", by C. Kirk Brown & others, for Prince Edward Island Energy Corporation.

"Wood Chip Drying Seminar", Proceedings compiled by E.T. Owens, of Research & Productivity Council, Fredericton, New Brunswick, Nov. 1986.

"A State of the Art Study of Residential Wood Chip Heating Systems", by D. Murray, for Energy Mines & Resources, Canada, March 1986.

"Factors Affecting the Occurrence of Fungi in Fuel Chips for Domestic Consumption", by Thomas Thornquist and Hans Lundstrom of The Swedish University of Agricultural Sciences, 1980.

"Fungi on Fuel Wood Chips in a Home", by J. David Miller and others, of University of New Brunswick, Jan. 1981.

"Small Scale Wood Chip Fuel Harvesting and Processing", by M. H. Schneider and others, of University of New Brunswick, Feb. 1985.

"Guide and Data Book", by American Society of Heating, Refrigerating and Air Conditioning Engineers, 1966 edition.

"An Overview of Achievements in Bioenergy Research, Development and Demonstration", by Passmore Associates International and Ensyn Engineering, Feb. 1987.

"The Economics of Integrated Full Tree Harvesting and Central Processing in Jack Pine", by Pierre Zundel,June '86.

"Residential Wood Fired Furnaces: A Demonstration of Advanced Systems" R.J. Brandon, Institute of Man and Resources, Charlottetown, P.E.I.

"Wood Fired Residential Heating Demonstration" Interim Report", Island Energy Associates, Oct. '79.

"Technical Evaluation of the Buck Rogers Gasifier" W.P. Walawender, Dept. of Chemical Engineering, Kansas State University, Jan. '83.

3.3 References cont.

"The Utilization of Forest Biomass and Forest Industry Waste for the Production and Conservation of Energy 1976", A. Carlisle, Environment Canada.

"Cost Benefit Analysis of Systems Using Flue Gas or Steam for Drying of Wood Waste Feedstocks", C. Mac Callum, B.R. Blackwell, L. Torsein, Sandwell & Company Ltd. ENFOR Project C-96.

"Drying and Storage of Woody Biomass Fuels" John G. Riley and Carl S. Drechel, Paper 83-3560, Am. Soc. of Agricultural Engineers.

"Air Convection in Self-Heating Piles of Wood Chips", Hans Kubler, Tappi, Aug.'82.

"Solid-Fuel-Fired Appliances for Residential Use" Canadian Standards Association, CHN 3-B366.1-M81 with supplements No.1-1985 and No.2-1986.

"Configuration of Small Scale Biomass Harvesting and Transport Systems, Kipping & Associates Ltd., ENFOR Project P-302.

"An Old Flame Rekindled - A Guide to Residential Wood Heating" Ministry of Energy, Ontario, ISBN0-7743.8094-2.

3.4 APPENDICES

APPENDIX A

CONTRACT DIRECTORY INFORMATION

TITLE: DESIGN OF A TREE CHIP DRYING SYSTEM

CONTRACTOR:

Intertech Engineering Corporation
199 Bay Street, Suite 503
Toronto, Canada, M5J 1L4

SCIENTIFIC AUTHORITY:

Dr. W.E. Lowe
Renewable Energy Division
Dept. of Energy, Mines & Resources
460 O'Connor Street
Ottawa, Ontario, K1A 0E4

PRINCIPAL INVESTIGATOR:

John Craig Cringan
(416)366-2135

CONTRACT NO:

DSS File No.51SZ.23216-6-6177

DURATION:

Commencement 86-07-17
Delivery Date 87-03-31

COST:

Fiscal Year 1986 - $88,838.00

OBJECTIVES:

- Determination of the real costs of drying wood chips on a cost net unit energy delivered basis as compared to costs for wet chips, and as a function of product flow rate; moisture content; temperature of drying; and flow rate of air.
- Determination of the drying characteristics of a dryer in terms of energy required to remove a pound of water at varying operating conditions of the dryer and product.
- Selection and design of a drying system for wood chips which gives the lowest cost per tonne of dried product.

Appendix A - Contract Directory Information cont.

RESULTS:

A study was completed on various types of dryers for tree chips in order to select and carry-out a detailed design of the most economically efficient dryer to incorporate in a chip drying system. The selected dryer is described as a medium temperature, regenerative type, with heat recovery via a tube in shell heat exchanger. The dryer has a nominal rating of 2000 pounds of water removal per hour with a net energy input of less than 1160 kJ/kg (500 BTU/pound). Detailed manufacturing drawings, procedures and specifications were prepared.

CONCLUSIONS:

A dryer for wood chips can be built for operation on a continuous basis at medium conditions of temperature and atmospheric pressure and at a lower total cost than high temperature or ambient temperature dryers.

The dryer can be optimized for varying moisture conditions of the product to produce chips with a constant moisture content of 25 percent.

With the design of dryer selected in this work, tree chips can be dried within the normal operating conditions by supplying less than 500 BTU of heat energy per pound of water removed from the chips. This is substantially less than alternative designs investigated.

RECOMMENDATIONS:

The use of latent heat for drying and preheating and the partial cooldown of the tree chips to achieve drying that recovers the energy of preheating, are features which distinguish this dryer from other thermal dryers and makes it very energy efficient. As a consequence this design of drying could become a standard in the future and so further development for other solid fuels should be investigated.